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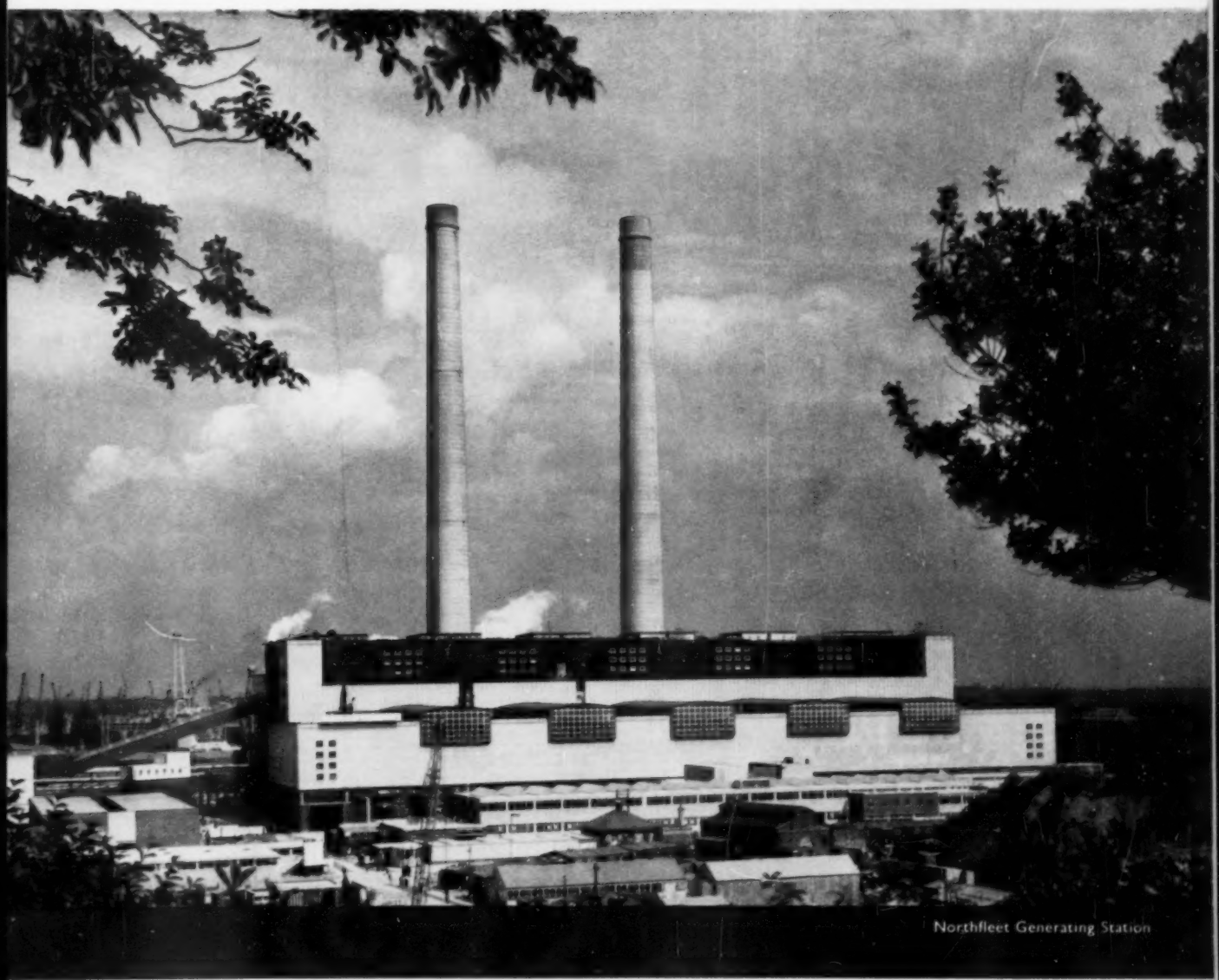

Northfleet Generating Station

THE GENERAL ELECTRIC COMPANY LIMITED OF ENGLAND

Volume 28, number 1

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COVER PICTURE

One of the new Thames-side generating stations of the Central Electricity Generating Board is at Northfleet where G.E.C. is installing six 120 MW reheat-cycle turbo-generators, designed for operation at 1500 lb/in² 1000° F with reheat to 1000° F at 375 lb/in². The first half of the station was commissioned during 1960.

Mr. Arnold Lindley, M.I.Mech.E., the new chairman of The General Electric Company Limited.

Arnold Lindley was born in Kent in 1902. He served his apprenticeship with the G.E.C., and after distinguished service with the Company in South Africa, was recalled in 1949 to become General Manager of the Erith Works. He was appointed a Director in 1953 and twelve months later assumed responsibility for the Company's atomic energy interests. In 1958 he was made an Assistant Managing Director in charge of the Heavy Engineering Group and was appointed Vice-chairman and a Managing Director in June 1959.

Hirst Research Centre

AFTER forty years of successful service to The General Electric Company Ltd., and indirectly to the electrical industry as a whole, the Company's Research Laboratories at Wembley have been given a new structure. They have been converted into a Research Centre, in which a number of autonomous research units, controlled by individual operating groups of the Company, can function side by side with other units serving the Company as a whole, and share common scientific and administrative services.

This development has yielded the opportunity to associate the Company's research activities with the name of the late Lord Hirst, founder of the Company, by giving to the Wembley group of Laboratories the title of Hirst Research Centre.

The G.E.C. is passing through a period of reorganization largely aimed at the decentralization of management. It now has seven main operating groups, each a complete unit for development, production and sales and enjoying a very large measure of autonomy. These are the Telecommunications and Electronics, Engineering, Domestic Equipment, Installation Equipment, Lighting and Heating, Osram, and Radio and Television Groups. The evolution of the Hirst Research Centre is a logical step following this reorganization.

There has been for a number of years a gradual tightening of the coupling between the Laboratories and the operating units of the Company which sponsor so much of their work. By the creation of the Research Centre the operating groups may now have research units under their own direct control, thus assuring themselves of the full benefits of decentralization. The units themselves, however, retain the advantages of centralization through their physical association at Wembley, instead of being scattered over the country at the various productive works.

Retention of the units in the new centre has the further advantage that continuity of work on existing projects is in no way disturbed by the change. Although the renaming of the Laboratories seems to suggest a full stop and restart, it is in fact merely a stage in a progressive operation which will not be completed for several years. The maximum flexibility is aimed at, and organization is being firmly subordinated to needs.

The first step under the new arrangements has been the formation of two main research units: the Central Research Laboratories and the Telecommunications and Engineering Research Laboratories, each under the control of a Deputy Director. Mr. O. W. Humphreys, C.B.E., B.Sc., F.Inst.P., M.I.E.E., now the Company's Technical Director, continues to act as Director of the whole centre.

Under Mr. V. J. Francis, B.Sc., A.R.C.S., F.Inst.P., M.I.E.E., the Central Research Laboratories will be responsible for most of the more fundamental research programmes, whether on behalf of the Company as a whole or of the operating groups or subsidiaries. They will provide specialized scientific and technical services and advice to the whole of the centre, and will ensure effective scientific liaison between all research units.

The Telecommunications and Engineering Research Laboratories, under Mr. R. J. Clayton, O.B.E., M.A., F.Inst.P., M.I.E.E., will be primarily responsible for work on behalf of the Telecommunications and Engineering Groups of the Company, and for fundamental researches in related fields. Mr. Clayton also holds the senior responsibility for administration of the centre.

Group research laboratories, each under its own manager, will be formed as and when individual operating groups of the Company so decide. Only one or two are expected to begin operations in the near future. Work for the operating groups which do not wish to set up their own research units immediately will be carried out for the time being by the two main Research Laboratories. Work under contract for the Government is not affected by the new arrangements.

In his announcement of the formation of the Hirst Research Centre, Mr. Humphreys emphasized that success in the electrical industry has always been closely linked with research. Today, when technology is advancing so rapidly on so many fronts, this is more than ever the case. Research has become increasingly complex and vastly more expensive, and the substantial sums necessary to finance new research can no longer be found from the narrow margins of profit from established products. New ventures must be self-supporting, which can be achieved only by early and profitable marketing.

It is precisely this need which has led to the reorganization of the Laboratories as a Research Centre. There can now be the utmost awareness of future possibilities from the earliest stages of research, continuing right through to the final engineering for production. The advantages gained by an early technical 'lead' will not be lost through any lack of communication.

At the same time, by collecting all the research effort into one centre, with full opportunity for liaison between the individual units, the very real danger of wasteful duplication of effort is avoided. Furthermore, problems presented to one research unit which fall more naturally within the ambit of another can be 'farmed out' to take advantage of expert knowledge which may be lacking in the original group.

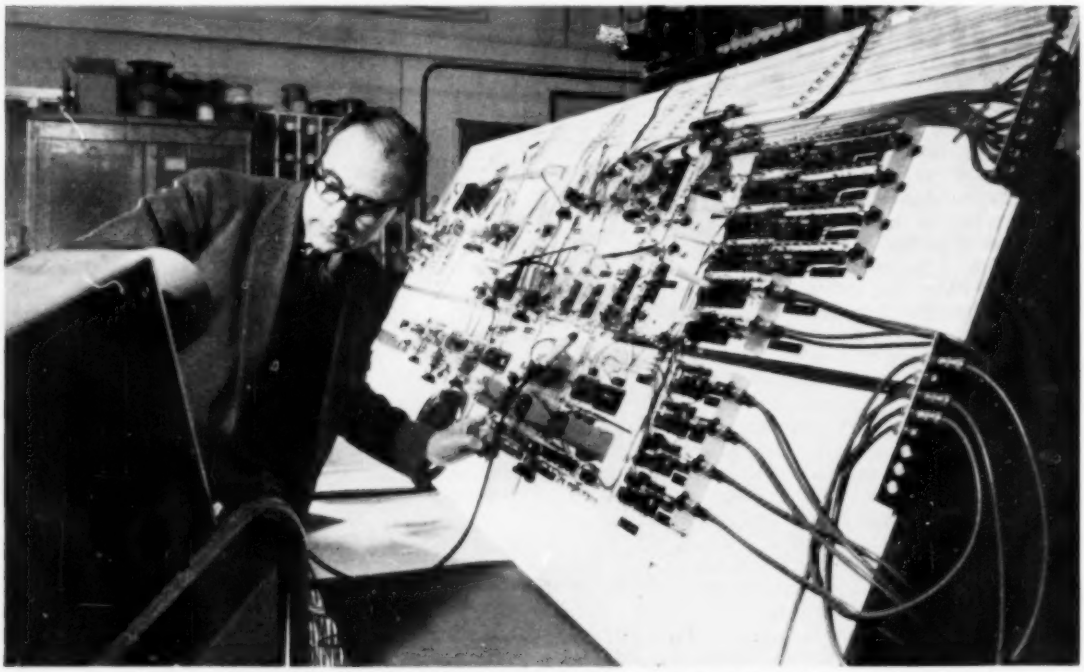
There is yet another advantage to this concept of an industrial research centre. Behind the work sponsored by individual operating groups of the Company are the extensive programmes of fundamental or long range research—not yet advanced to a stage at which their results can be applied to any one group—which are

undertaken on behalf of the Company as a whole. Senior scientists who are fully aware of the Company's interests and forward-thinking plan these programmes, from which are derived the scientific discoveries and inventions which open out new vistas of production. This is the basis of continuing leadership in technology.

With the physical association of the group research units with the Central Research Laboratories, in which these long-range programmes are carried out, all the current applied research, right through development to quantity production, can take immediate advantage of the latest scientific and technological discoveries and ideas. The group research units can also make full use of the best advisory and technical services the Company can provide.

The creation of the Hirst Research Centre is an important experiment in industrial research which will be watched closely by many large companies throughout the world. That it is being applied to a research establishment which has already acquired an enviable world-wide reputation demonstrates great confidence in its outcome.

Impermeable graphite for use in nuclear reactors is being developed at the Hirst Research Centre. In this demonstration air is pumped into normal and treated graphite specimens to show the difference in permeability.



Experimental apparatus used by the Electronic Switching Group at the Hirst Research Centre in the development of electronic telephone switching networks.

Self-excitation of Alternators by Static Exciters

By D. C. GILCHRIST, B.Sc., A.M.I.E.E., Engineering Group, Witton.

THE excitation current for a d.c. generator can be readily obtained from its own output by the simple and commonly used method of connecting the field winding across the generator armature voltage. This self-excitation system can provide a reasonably steady terminal voltage at all loads since the inherent regulation of a d.c. generator is fairly small. The voltage change with load can be made even less by passing the generator output current through a few compounding turns wound round the field poles, so boosting the excitation as the generator is loaded. Alternators, unfortunately, cannot be self-excited quite so easily. To derive the d.c. excitation current from the a.c. output of the alternator a rectifier must be used and this introduces a difficulty in the initial build-up of excitation. The inherent regulation of an alternator is much greater than that of a d.c. generator and it is not possible to use ordinary compounding turns on the field poles. It has therefore been usual to obtain the field supply for an alternator from a small d.c. excitation generator. When constant alternator voltage is required with varying load without manual adjustment, then some form of automatic voltage regulator (a.v.r.) must be employed.

The problems in the self-excitation of alternators can however be overcome by certain quite simple but ingenious circuits which use only static components. For quite a wide range of applications these static systems can have distinct advantages over systems involving a d.c. exciter and an a.v.r. The basis of most of these circuits is to supply the no-load excitation by connecting the field supply rectifier in series with an impedance across the alternator terminal voltage. When the alternator is loaded the output current flows through a transformer which injects a further current into the field rectifier. By correct choice of circuit this can be made to give approximately the correct excitation for all loads and power-factors. Automatic control circuits can be added to this basic system to give high-accuracy voltage regulation. Static excitation circuits have been in use for some time but recently these systems have been coming into greater prominence. They have been used during and after World War II on small generators for military applications, where their simplicity, robustness and freedom from maintenance are useful assets. More recent but now well-established applications are the static excitation of marine alternators and the quick-acting and precise control of high-frequency generators.

EXCITATION CHARACTERISTICS OF ALTERNATORS.

If the terminal voltage of an alternator is to be kept constant when load is applied, the excitation must be increased to overcome the voltage drop due to the synchronous impedance. Since the synchronous impedance is mainly inductive, the effect of the voltage drop is much greater for lagging power-factor loads than for unity power-factor loads. This effect is shown in the simplified vector diagram of an alternator (fig. 1).

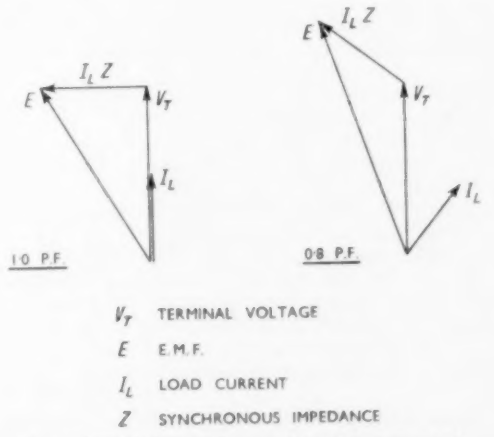


Fig. 1.—Simplified vector diagram of an alternator on load.

As the alternator is loaded the excitation has to be increased to produce a higher effective e.m.f. E. The magnitude of this effective e.m.f. can be found for any load by adding the synchronous impedance drop $I_L Z$ to the no-load terminal voltage V_T, as illustrated in the vector diagram. The e.m.f. is approximately proportional to the excitation current and so the vector

diagram also indicates the required change of excitation with load.

Any static excitation system which uses the load current to boost the excitation must, to be effective, take into account both the magnitude and the power-factor of the load. In a practical design of alternator,

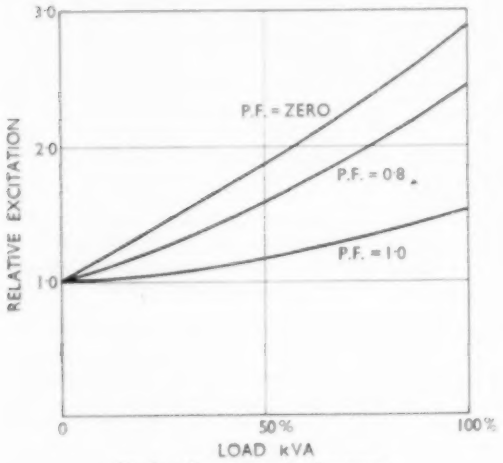


Fig. 2.—Alternator excitation curves.

saturation will cause the synchronous impedance to change with load. It will also affect the linearity of the relation between e.m.f. and excitation current. Typical practical curves of the variation of excitation with load for constant terminal voltage are shown in fig. 2.

Transient Conditions.

When a load is suddenly applied to an alternator some transient disturbance of alternator voltage is unavoidable whatever form of voltage regulator is used. In many applications it is important that the peak magnitude of this disturbance should be kept to a minimum and the alternator voltage restored to its normal value as quickly as possible. The effect that the choice of excitation system can have on this transient disturbance is illustrated in fig. 3.

When the excitation supply to the alternator is kept constant the voltage fall will occur in three significant stages:

(*a*) An instantaneous fall due to armature leakage inductance and corresponding to the alternator subtransient reactance.

(*b*) A further fall occurring, as eddy currents die away, with a very short time-constant, normally, of the order 0·01 to 0·04 second. After this has taken place the total fall corresponds to the alternator transient reactance.

(*c*) A comparatively slow fall, caused by armature reaction, occurring as the induced current in the excitation circuit dies away.

In the example shown in fig. 3 the sub-transient reactance is responsible for a drop in voltage of 10%, the transient reactance for a total of 15% and the synchronous impedance for the final steady fall of 40%.

With a moderate-response excitation system and an automatic voltage regulator, the field forcing voltage will be applied a short time after the first two stages have taken place. The peak dip occurring will be rather greater than that due to transient reactance but much less than the full drop due to synchronous impedance.

High-response excitation systems, on the other hand, can apply field forcing almost at the moment at which load is applied. The peak dip will be no greater than that due to transient reactance and recovery to normal voltage can be made very rapidly. In certain static excitation systems the build-up of load current is arranged to force an increased current into the field, over and above that due to armature reaction. Thus it is possible to reduce the voltage dip to slightly less than that given by transient reactance. However, because of eddy currents in the field magnetic circuit, it is not possible to reduce the dip to the value given by sub-transient reactance alone.

Static Excitation of Alternators.

Several different excitation circuits are known which give full compensation for the magnitude and power-factor of the load. A detailed description of one particular type will illustrate the general principles involved. One elegant but simple example of these is the G.E.C. Accurex I static exciter, the circuit diagram of which is given in fig. 4. From this it will be seen

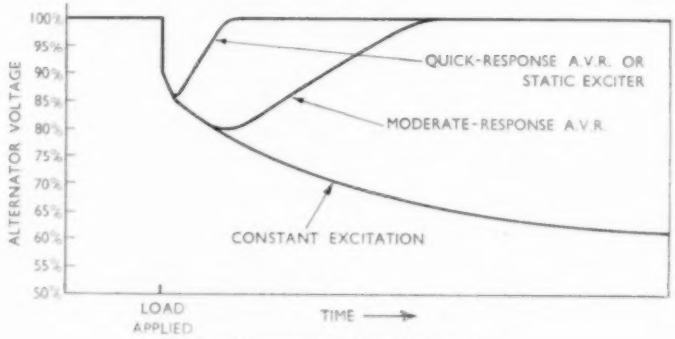


Fig. 3.—Alternator transient voltage response.

that only four components are required for the self-excitation of a single-phase alternator. The compounding current transformer CT has two primary windings, a series primary, carrying the alternator load current and a shunt primary carrying a current derived

from the terminal voltage of the alternator by the circuit comprising the reactor L and the capacitor C. These two currents are summated in the transformer and the resultant vector sum is supplied by the secondary to the rectifier MR which, in turn, supplies the d.c. excitation current to the field windings.

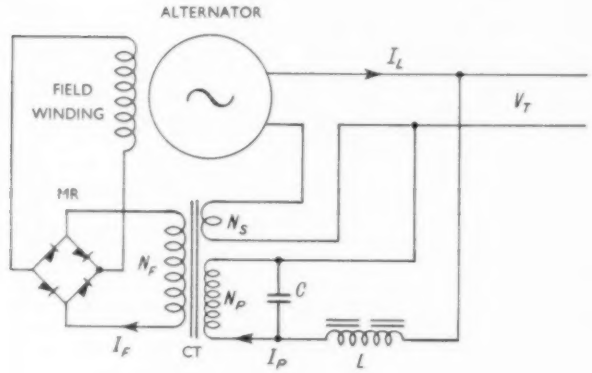


Fig. 4.—Accurex I static exciter for single-phase alternator.

The action of the shunt circuit can best be described by considering first the circuit shown in fig. 5. If the reactor and capacitor are designed to have approximately equal impedances at the normal frequency of

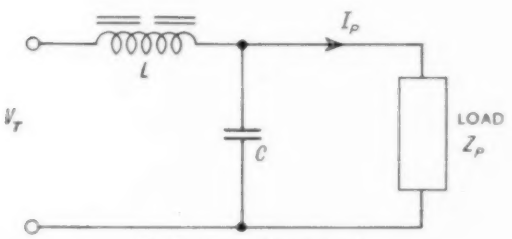


Fig. 5.—Shunt primary circuit.

the supply, then the current fed into the impedance Z_P will be given by the equation:

$$I_p = \frac{V_T}{j\omega L}$$

Hence, this current is proportional to the applied voltage and lags 90° behind it, but is independent, within practical limits, of the magnitude and phase angle of the load. This effect is generally known as the Boucherot effect and can easily be proved by analysis of the circuit. It can be appreciated qualitatively by considering that, as the load impedance is increased, the reactor and capacitor will tend to go further into resonance, so increasing the load voltage.

Applying this result to the static exciter circuit of fig. 4 shows that the shunt primary winding of the current transformer CT will be supplied with a current proportional to, and lagging 90° behind, the alternator terminal voltage. Hence, when the alternator is unloaded, its excitation current will be proportional to its terminal voltage, as illustrated in fig. 6. The slope of this characteristic can be controlled by the choice of the impedances of L and C and by the primary turns used on the CT and so it can be designed to cut the open-circuit magnetization curve of the alternator at the required open-circuit terminal voltage.

When the alternator is loaded, its excitation is automatically boosted by the current flowing in the series turns on the compounding transformer. This is illustrated in the vector diagrams shown in fig. 7. The current in the shunt primary will lag the terminal voltage V_T by 90°. The angle between the $I_L N_S$ and $I_P N_P$ vectors in fig. 7 will therefore be the same as that between the vectors V_T and $I_L Z$ in fig. 1. By the correct choice of the series turns N_S the corresponding vector triangles in these two figures can be made similar triangles. Since the vector $I_P N_P$ has been designed to give the excitation for the no-load terminal voltage V_T,

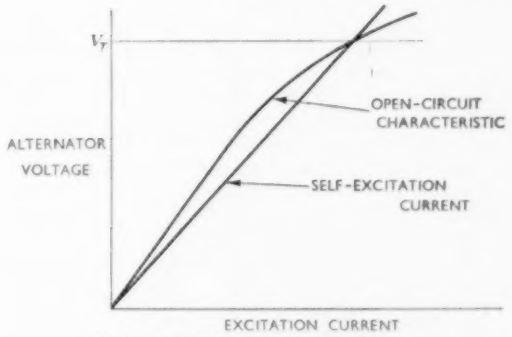


Fig. 6.—Self-excitation characteristics.

the resultant vector $I_F N_F$ will give the correct excitation for the effective e.m.f. E required for this terminal voltage at any load and power-factor.

In a practical design the compounding turns are chosen to give the best overall result taking into account all non-linear effects such as saturation. Typical output voltage characteristics for a 6 kVA 230 V single-phase alternator controlled by an Accurex I static exciter are shown in fig. 8. A voltage regulation accuracy of ±3% is achieved under all conditions of load and power-factor.

All practical forms of rectifier have non-linear characteristics at low applied a.c. voltages. No d.c. current will be produced until the a.c. voltage has reached some definite value. The residual voltage of an alternator may be only about 1% of its normal value and difficulties will arise with initial build-up of alternator voltage unless something is done to feed an amplified residual voltage to the rectifier. This presents no problem in the circuit just described, since the resonance effect of L and C when loaded with a high impedance will provide just such an amplified voltage.

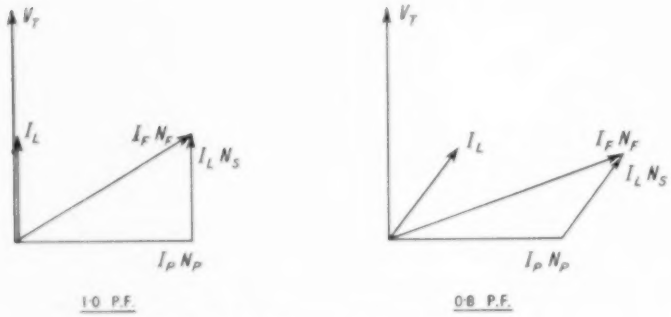


Fig. 7.—Vector diagram of Accurex I static exciter.

The currents in both the shunt and series primaries of the compounding transformer are independent of the field resistance. Hence changes of ambient temperature and self-heating of the field windings do not affect the excitation current.

From the equation for I_P given on page 7 it will be seen that this current, in addition to being proportional to V_T, is inversely proportional to frequency. Hence, as the alternator speed is increased the circuit automatically reduces the excitation current in proportion, so tending to keep the terminal voltage constant.

For 3-phase alternators a 3-phase version of the circuit described above is normally used, though for small alternators with balanced loads, it is still possible to use a single-phase excitation circuit.

The main features of this type of simple static exciter are summarized below:

(*a*) Moderate voltage regulation accuracy.
(*b*) High speed of response.
(*c*) Minimum transient voltage dip.
(*d*) Unaffected by ambient temperature and self-heating.
(*e*) No moving parts.
(*f*) Uses only a few robust components.
(*g*) High reliability and freedom from maintenance.
(*h*) Requires no protective devices such as an over-voltage relay.

The applications for which this circuit is best suited follow almost automatically from these features. In general for any application of small and medium-size alternators requiring good quality equipment with moderate accuracy and high reliability, this static exciter has advantages over an exciter-a.v.r. combination. It has been used, for example, on many mobile generator sets and on auxiliary generator sets for industrial use.

Because of the need for designing the static exciter to match accurately the alternator characteristics, any price comparison with an exciter—a.v.r. combination will tend to be more favourable to the static exciter where reasonable quantities of the same alternator design are required.

Alternators controlled by Accurex I static exciters may be made suitable for parallel operation, either by designing to give a drooping characteristic at low power-factor lagging loads, or by arranging to parallel the field windings of the alternators. The series compounding ensures that excitation is maintained under short-circuit conditions and that rapid voltage recovery occurs on removal of the short.

Voltage trimming resistors allowing a small range of adjustment of the controlled alternator voltage can be included in the Accurex I circuit. This facility, however, is gained at the expense of the otherwise extreme simplicity of the circuit.

G.E.C. RANGE OF ACCUREX STATIC EXCITERS.

The absence of a rotating d.c. exciter and the general freedom from moving parts and, hence, maintenance, make static excitation an attractive proposition in a wide range of applications. However, a number of important applications have requirements which cannot be met by the Accurex I static exciter described

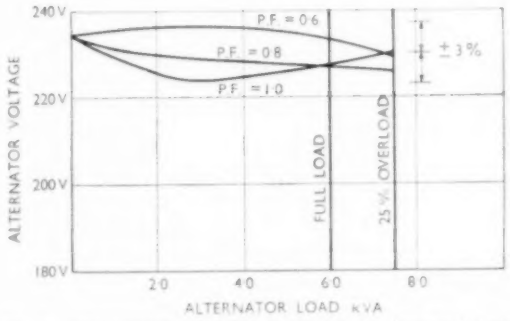


Fig. 8.—Characteristics of 6 kVA alternator with Accurex I static exciter.

in the previous section. These include, for example, all applications where very close voltage control is required. For medium-size alternators above about 50 kVA, some degree of manual voltage adjustment is generally desired, and for these sizes of machines this facility cannot easily be added to the basic Accurex I circuit. To cater for these conditions two other types

of Accurex static exciter have been developed, each with a wide but distinct field of application.

Accurex II Static Exciter.

This is a development of the Accurex I circuit intended for applications requiring close voltage control. A typical circuit diagram is shown in fig. 9. The same four basic excitation components are used but these are now designed so that the secondary current of the CT, both on no-load and on load, is always slightly higher than that necessary to supply the required excitation. The excess current is shunted off by a control circuit connected in parallel with the secondary of the CT. To obtain a high degree of accuracy a closed-loop system of control is employed. The alternator voltage is rectified and smoothed and is then compared with a constant-potential reference voltage. In the example shown an accurate voltage-reference neon tube is employed. At

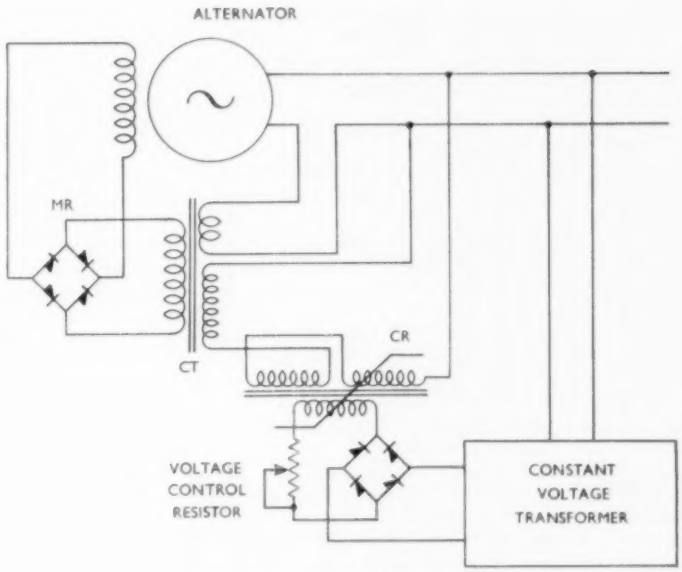


Fig. 10.—Accurex III static exciter.

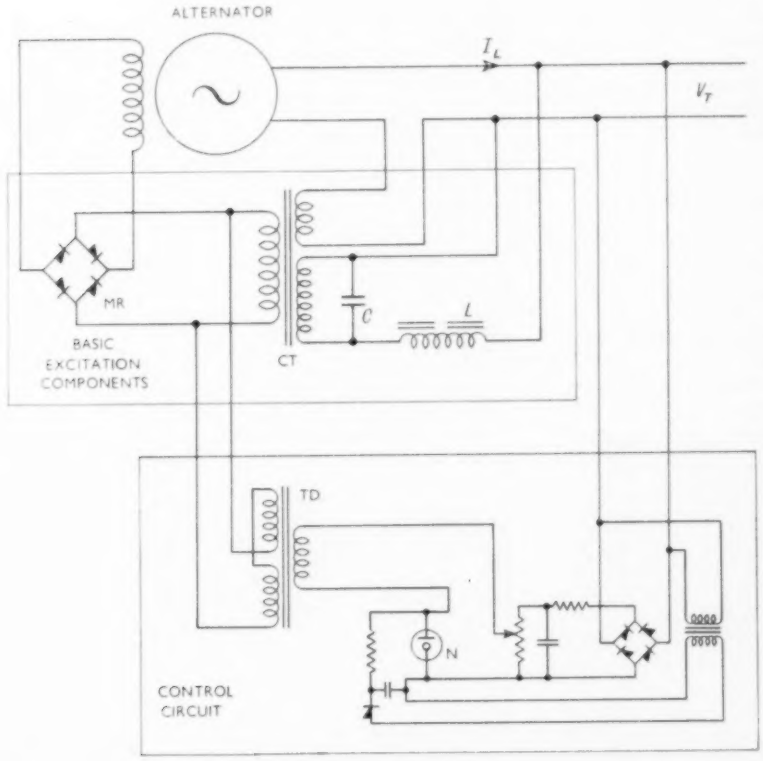


Fig. 9.—Accurex II static exciter.

normal alternator voltage these two direct voltages are nearly equal. However, if the alternator voltage changes with load due to imperfections of the basic excitation circuit, then a current will flow in the d.c. input coils of the transductor TD. This adjusts the a.c. current taken by the transductor from the secondary of CT and so can trim the alternator excitation until the voltage is restored to very nearly its correct value.

Voltage regulation accuracies of $\pm 1\%$ are readily obtained with this circuit. Speed of response is very good, being rather better than that obtainable with the Accurex I. Since a low-power voltage sensing circuit is used, features such as line drop compensation can be easily added. A control circuit using silicon controlled rectifiers and transistors can be used as an alternative to the transductor circuit described above. This enables a saving in the size and weight of the control circuit to be made.

Although the Accurex II circuit is more complex than

the Accurex I, it is still a completely static equipment. An example of the application of this type is to the control of alternators providing accurately regulated high-frequency power supplies for radar, computers, etc.

Accurex III Static Exciters.

While the Accurex I static exciter has been used on alternators as large as 400 kW, most applications for generators above about 50 kW have requirements which are best met by a slightly different form of self-excitation circuit. To meet this need the Accurex III static exciter has been developed. A basic circuit diagram of this type is shown in fig. 10. A single-phase circuit has been shown for simplicity of explanation but this static exciter is mainly used for the control of 3-phase generators.

The circuit differs from the Accurex I in that the capacitor of the resonant circuit is omitted and the linear reactor is replaced by a d.c. controlled saturable reactor (transductor) CR.

Although the capacitor has been omitted, the basic circuit can still give the correct alternator excitation for all load power-factors. However, certain stability limits are now introduced which must be avoided by correct design of alternator and static exciter. The advantage of the Accurex III circuit lies in the possibility of trimming the alternator excitation as desired by adjusting the d.c. excitation of the controlled reactor.

Since the capacitor has been omitted, this static exciter requires an alternative means to ensure initial build-up of excitation. This may be done by a relay which temporarily connects the alternator residual voltage to a low tapping on the primary of the CT, so giving the desired relative amplification of the residual. In applications where a relay is undesirable a small auxiliary resonant circuit is used for starting.

Where accurate automatic voltage regulation is not required the d.c. excitation can be supplied from the rectified output of a constant voltage transformer as shown in fig. 10. Trimming of the alternator excitation can then be effected by adjusting the variable resistor in series with the d.c. excitation winding of CR. This static exciter is particularly suited to medium power generating installations where the mean normal load on the alternator changes only slowly, but which may be suddenly called upon to supply a heavy overload current at low power-factor, for example when a large induction motor is started direct-to-line. A very occasional trimming of the voltage control will keep the alternator voltage accurately at its correct value, while under abnormal load fluctuations the inherent regulating properties of the circuit permit only a small deviation of the alternator voltage from its correct value.

When accurate voltage regulation is required then the d.c. excitation of the saturable reactor CR can be controlled by a voltage regulating circuit, such as has been described for the Accurex II. Magnetic-amplifier control circuits have been most widely used in the past but transistor control circuits are now being increasingly used. Applications where the Accurex III with accurate automatic voltage regulation has been used include the control of 40 to 100 kW 400 c/s 3-phase alternators used for ground power supplies for aircraft.

Direct Self-Excitation of Alternators.

The three Accurex self-excitation systems already described all use compounding from the output current of the alternator. If this is omitted and the alternator is self-excited only by a shunt circuit from its terminal voltage, then some method of automatically controlling the alternator voltage is almost essential. The need for a wide range of current control makes the task of the controlling element very onerous, and, in the past, this system has only occasionally been used.

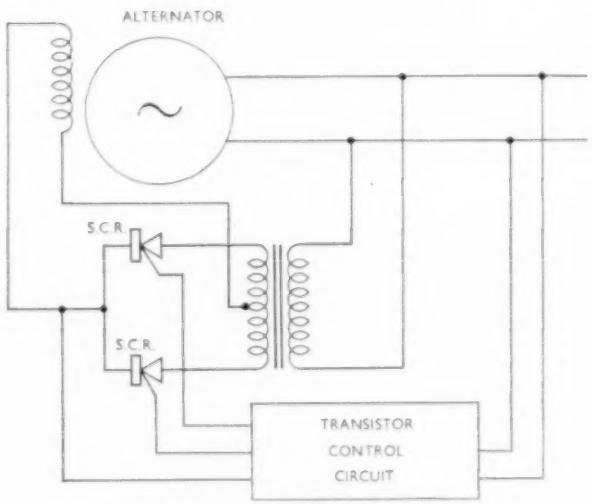


Fig. 11.—Direct self-excitation of an alternator by means of silicon controlled rectifiers.

With the development in recent years of the silicon controlled rectifier, a controlling element has become available which is quite suitable for this onerous duty. At the same time the almost instantaneous response of this control when driven by a transistor automatic control circuit allows field forcing to be applied almost as quickly as with a current-compounded circuit. A typical example of this type of circuit, which has already been applied to several different generators, is shown in fig. 11.

For generators of a high-rated current output the absence of the need for taking the output current through the control circuit is an advantage. It also allows a much greater degree of standardization to be obtained between the equipment for generators of different ratings and frequencies. By correct choice of the field voltage or by the use of tappings on the armature winding of the alternator it is possible to

dispense with the excitation transformer shown in fig. 11. No large iron-cored components are then used in the circuit, which can therefore be made very light and compact.

This system is not suitable for applications where excitation must be maintained when the alternator is short-circuited, since all the excitation supply is lost under these conditions.

IMPORTANT APPLICATIONS.

The following examples have been chosen to illustrate further the type of application which can benefit from the adoption of static excitation:

Static Exciters for Marine Alternators.

The use of alternating current for the electrical installations of merchant ships has been increasing greatly over the last few years. To take full advantage of the smaller size and reduced complexity of a.c. motors and switchgear, direct-to-line starting is almost always used for auxiliary motors driving winches, pumps, etc. These motors take a large, low power-factor starting current and it is important that the disturbance to the ship's supply caused by starting these motors should be kept to a minimum. The quick-response excitation given by a static exciter, together with its general freedom from maintenance, makes it especially suitable for the control of alternators used for these marine installations. The elimination of the d.c. exciter is an important advantage not only on the grounds of reduced maintenance, but also in reducing the overall length of the generator set, which has often to be fitted in a limited space.

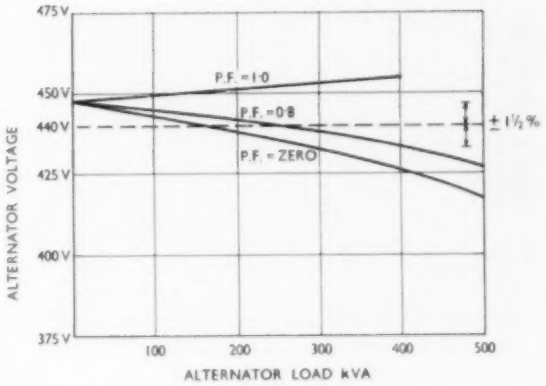


Fig. 13.—Characteristics of 400 kW alternator with Accurex III static exciter.

Accurex III static exciters have already been installed both on dry-cargo ships and on tankers (fig. 12). Since the mean load on the ship's electrical system is normally fairly constant, especially when the ship is at sea, the simpler of the two Accurex III systems is normally used, i.e., the system in which the d.c. excitation of the controlled reactor is manually controlled. Fig. 13 shows typical voltage/load characteristics for a 400 kW marine alternator, taken with the manual control adjusted for normal voltage at half the rated load. These results take into account the drooping speed characteristics of the prime mover. Between one-quarter and three-quarters full load at rated power-factor the voltage regulation is kept within $\pm 1\frac{1}{2}\%$ of the correct voltage, and so no trimming of the voltage control is normally required. For low

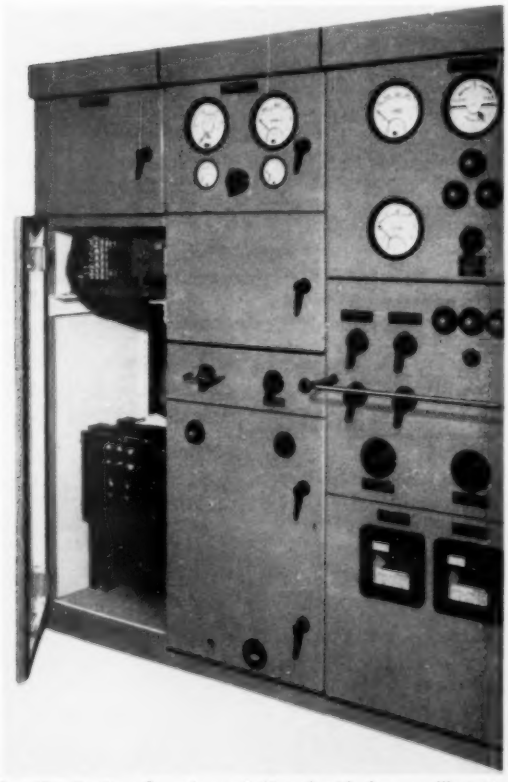


Fig. 12.—Section of marine switchboard with Accurex III static exciter.

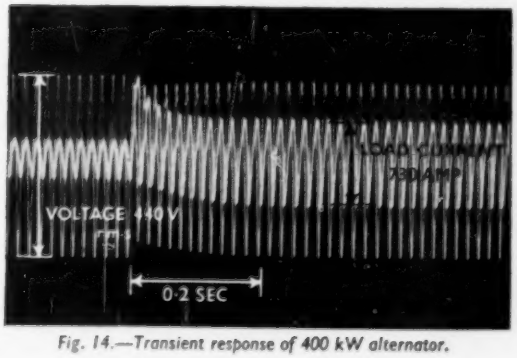


Fig. 14.—Transient response of 400 kW alternator.

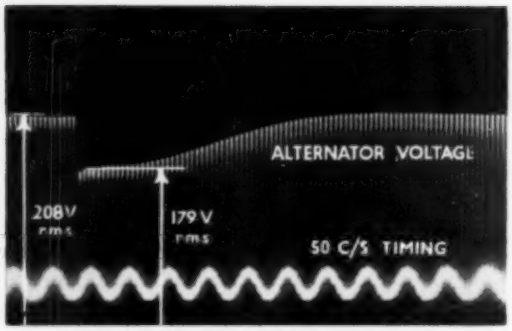


Fig. 15.—Transient response of a 60 kVA 400 c/s alternator.

power-factor loads a distinct droop is given to the characteristic to ensure that all the alternators on board the ship can be operated in parallel.

The oscillogram shown in fig. 14 is the response of this alternator when a 400 kVA load of low power-factor is suddenly applied, on top of a base load of 200 kW at 0·8 power-factor. The initial dip of voltage is only 14% and the recovery of the voltage starts within a cycle of the load application. Within 0·2 second the voltage has reached its final steady value.

Oscillograms of single- and 3-phase short-circuits show that the initial current peak is no greater than with separate excitation. This is to be expected since the static exciter cannot affect the alternator sub-transient reactance. There is therefore no need to uprate switchgear because a static exciter is used.

The Control of High-frequency Generators.

During World War II the advantages of high-frequency power supplies for many military applications were clearly realized. Equipment could be smaller and lighter and capable of faster response to control signals. These factors were of vital importance in front line equipment, especially in aircraft. Quite a variety of different frequencies came into common use at that time.

In more recent years high-frequency power supplies have been widely used for industrial automatic control equipment and they are now being adopted for some civil aircraft. A much greater degree of standardization of frequencies has been achieved and 400 c/s is now by far the most widely used. Certain higher frequencies, particularly 1600 c/s and 2400 c/s are also in use for special control applications. For induction heating even higher frequencies are normally used.

Since high-frequency alternators can be made with quite short field time-constants, quick-response d.c. exciters must be used if the full performance of the alternator is to be realized with an exciter-a.v.r. combination. On the other hand, the speed of response of a static exciter control system increases with frequency, while the size and weight of the components decrease. These reasons, together with the usual advantages of a static circuit, have resulted in the wide adoption of static excitation circuits for the control of high-frequency generators.

Most applications for h.f. alternators call for accurate voltage regulation. Hence, the Accurex II or the Accurex III static exciters with automatic control are normally used. The oscillogram in fig. 15 is the response of a 60 kVA, 208 V, 3-phase, 1500 rev/min, 400 c/s alternator with Accurex III static exciter used for ground power supplies for aircraft.

For a sudden application of full load at 0·8 p.f. the maximum voltage dip is 14% and recovery to normal voltage occurs within 0·12 second. In this equipment the voltage is regulated to an accuracy of $\pm 1\%$ for all conditions of load, power-factor and ambient temperature. The alternator waveform is closely sinusoidal under all conditions of resistive and reactive load. Low alternator leakage reactance ensures that little distortion of the waveform occurs when a non-linear load is connected to the alternator.

The trailer shown in fig. 16 is a mobile motor-generator set including a 5 kW 2400 c/s single-phase alternator with an Accurex II static exciter. The alternator voltage is regulated to an accuracy of $\pm 1\%$ under the most severe conditions and the speed of response to moderate load changes is better than 50 milliseconds.

Mobile Generator Sets.

Many mobile generator sets have to operate under very arduous conditions. The same set may have to work outdoors in arctic, tropical, high-altitude and even desert sand storm conditions. For such sets the advantages of a control system having no moving parts are very clear. The high field excitation provided by static exciters under conditions of heavy overload is also very useful, since the generators often have to start induction motors with a rating almost as large as the generator.

In one application over 2000 single-phase 6 kVA 50 c/s alternators with Accurex I static exciters have

Fig. 16.—Trailer-mounted M.G. set with Accurex-controlled 5 kW 2400 c/s alternator.

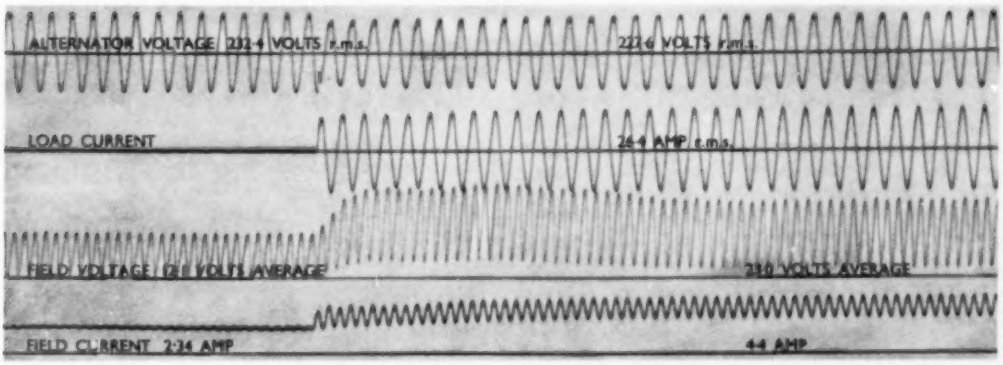


Fig. 17.—Transient response of 6 kVA 50 c/s alternator with Accurex I static exciter.

TABLE 1.
STATIC EXCITER APPLICATIONS.

Alternator Size	Accuracy of Voltage Control Required	Field of Application		
		Accurex I	Accurex II	Accurex III
Up to 50 kW	Moderate	Single- and three-phase-alternators. Power frequency and high frequency.	Some applications to special high-frequency alternators.	—
	Precision	—	Single-phase alternators power frequency and high frequency.	Three-phase alternators power frequency and high frequency.
50 kW to 1000 kW	Moderate	Some applications to single-phase alternators.	—	Three-phase alternators power frequency and high frequency.
	Precision	—	Some applications to single-phase alternators.	Three-phase alternators power frequency and high frequency.

been made for a customer who required the utmost simplicity in operation and maintenance. A petrol engine drive was used and the whole unit was mounted on a trailer to form a completely self-contained and virtually foolproof mobile power supply. The design has proved to be very successful and the units are operating under widely varying conditions all over the world. The accuracy of voltage control obtained was well within the $\pm 5\%$ specified. An oscillogram of the voltage response on switching on full load at 0·8 power-factor is shown in fig. 17. This shows that the voltage recovers to within 5% of the nominal within 0·18 second. Self build-up has been found extremely reliable on these machines, no trouble having been experienced, even with new equipment. All alternators and static exciters of this design are fully interchangeable.

CONCLUSIONS.

The field of application of each of the three Accurex static exciters has been generally indicated in the foregoing sections. Since these fields overlap to some extent the choice of static exciter will depend on the particular operational and economic requirements of each application. Nevertheless, a broad summary of the position as set out in Table 1 may act as a useful guide. The choice between a static exciter and alternative excitation systems will be dictated by the importance of the features outlined above to the application being considered. It is probable that static exciters would be employed more widely were their potentialities and advantages more generally appreciated.

Progress at Hunterston

By D. W. T. ANGWIN, B.Sc., A.M.I.Mech.E., Chief Resident Engineer,
Hunterston Nuclear Generating Station.

THE major portion of the civil engineering work on the two reactor structures and the turbine hall of the Hunterston Nuclear Generating Station was completed by January, 1961. Around these main structures the various subsidiary buildings are taking shape amid the temporary huts and workshops dotted all over the site. The station, which is situated on the Ayrshire coast, some thirty-five miles south-west of Glasgow, Scotland, is being built for the South of Scotland Electricity Board.

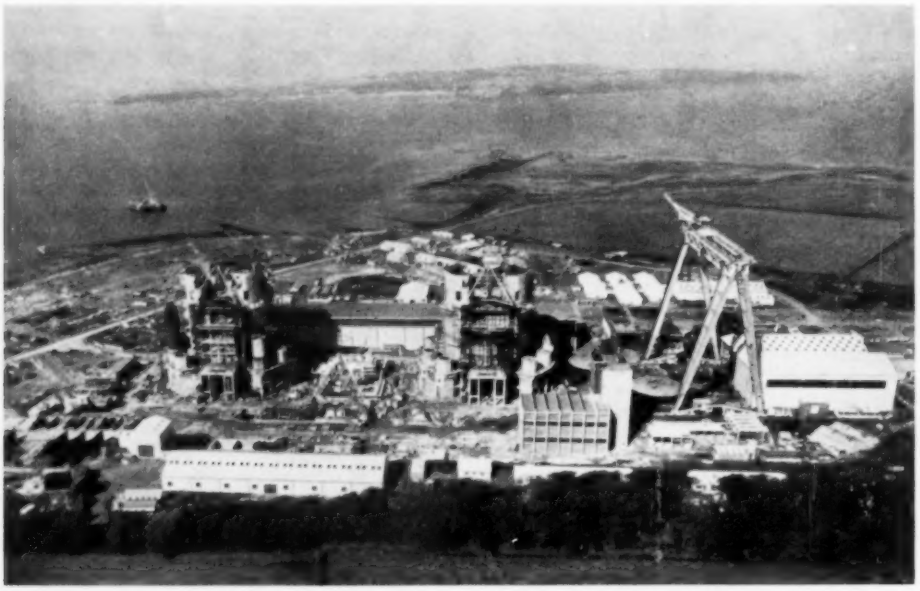


Fig. 1.—Aerial view of Hunterston Nuclear Generating Station, August 1960.

An aerial view of the site is shown in fig. 1, and some facts and figures relating to the construction of the station are given in Table 1.

Externally, there is little to choose between the appearance of the two reactor structures which tower some 180 ft above the site. The height of the second reactor structure has, until recently, been limited by the necessity to lift parts for the first reactor across it.

The last large sections of the concrete biological shield of the first reactor have been lifted into position and a start has been made on the erection of the structure to house the service machine. This machine is being assembled for testing at the Erith Works of the Company and the gantry has been received on site.

The emphasis on construction has now moved away from civil engineering to mechanical engineering, with the fabrication and installation of the pressure vessels, steam-raising units, and mechanical and electrical plant taking pride of place.

Inside the first reactor structure, the assembly of the 3 in. thick, 70 ft diameter pressure vessel is complete, all courses having been placed and welded together, with the core-support grid and inner heat shield located inside the vessel. The vessel is now being prepared for stress-relief.

The supporting skirt of the second reactor pressure vessel has been fabricated *in situ* inside the biological shield and the combined bottom head and support course and equator course have been lifted into position, together with the support grid and course three.

Elsewhere on the site fabrication and assembly of the steam-raising units has been going ahead; a number of the 210 ton vessels have been stress-relieved and

TABLE 1.

Area of site	... 110 acres
Reclaimed from sea	... 17 acres
Rock excavated	... 174 000 cu yd
Total steel used (estimated) ...	... 17 000 tons
Total concrete poured (estimated) ...	... 185 000 cu yd
Weight of each reactor (including pressure vessel and contents) ...	... 80 000 tons
Installed capacity (electrical) ...	... 360 MW
New roads on site	... 4 miles
Men working on site (*a*) Peak ...	... 2500
(*b*) At present	... 2300
Principal Contractors:	
The General Electric Co. Ltd. (main contractor)	
Simon-Carves Ltd.	
Motherwell Bridge & Engineering Co. Ltd.	
Mowlem (Scotland) Ltd.	

hydraulically tested and are now in the final stages of construction, which includes nuclear clean conditioning. Several steam-raising units associated with the first reactor have been accepted and lifted by the Goliath crane on to their plinths and tubing and erection of the gas circulating installation is proceeding as planned. Much of the clean-conditioned gas ducting linking the reactor pressure vessel with the steam-raising units has been erected, together with the associated gas valves and bellows; the whole is gradually being enfolded by the encroaching reactor building steel work. Externally, the 680 ft long turbine hall appears complete, although internally much work is in progress. Four of the six condensers are installed, while the foundations for the turbo-generators are ready for the installation of the sets themselves and the first machine is being erected.

Further down the coast, to the south of the main part of the site, is the circulating water pump-house. This building is finished and much of the equipment, including pumps, motors, bandscreens, valves, filters, etc., is installed. The associated culverts and tunnels on the intake side of the circulating water system have been completed. On the outfall side, some 600 yards further up the coast, the tunnels have been driven and are now being lined and the siphon seal is almost finished, bringing the end of civil work in this area in sight.

TECHNICAL DETAILS.

Reactor A.

On the north and south sides of the now completed concrete biological shield the adjoining 'reactor building' and 'exit building' are being constructed. The steel frames for both buildings were finished some time ago, and much progress has been made with the intermediate floors, brickwork, stairs and lift shafts. On the other two faces of the biological shield the eight concrete plinths and their connecting floors are ready for the remaining steam-raising units. All the seal oil pumps, tanks and coolers have been installed at the various levels in the reactor structure.

Much of the concrete structure upon which the tracks of the service machine will be mounted has been built. The 150 ton machine will be situated at the 178 ft 6 in. level above the biological-shield roof of the reactor, and will have longitudinal and cross-traverse facilities.

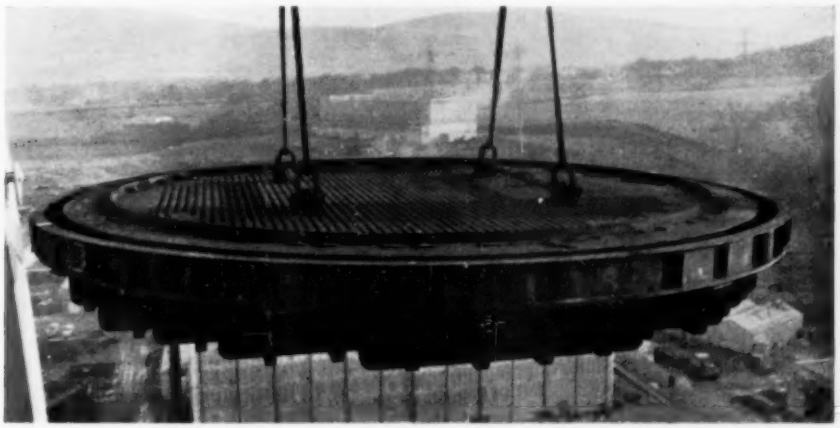


Fig. 2.— Lifting the 340 ton core-support grid of Reactor B into position inside the pressure vessel.

A rehearsal shaft for the charge machine is included in the reactor structure and the civil engineering for this is finished. It will be able to test every function of the charge machine and is expected to be used daily when the station is in operation. Other completed work associated with the charge machine includes the installation of the turntable tracks, roller path, cooling and shielding water tanks, and the fitting of the 170 ton exit shielding door.

With the circumferential welding between the various courses of the reactor pressure vessel finished

and the welding in and non-destructive testing of the charge nozzles and control rod nozzles also completed, the time for stress-relief of the whole structure is approaching. Electrical resistance heating will be employed for this operation, which will then be followed by final installation work and a pneumatic pressure test. This test consists of subjecting the sphere to an internal air pressure of 253 lb in^2 and checking for leaks. All this work will be completed and graphite laying will begin in October, 1961.

The top inner surface of the pressure vessel is to be cooled by diverting some of the incoming CO_2 coolant gas through a system of pipes suspended between the inner heat shield and the pressure vessel dome. These pipes, which are perforated on the upper surfaces to permit the escape of the coolant gas, have been erected.

Closing in of the reactor structure with precast concrete units which form the soffit of the roof biological shield has progressed. Six inverted double-webbed T-beams are being used for this purpose, and they span the aperture, being supported at each end on a 308 ton member. Some of these T-beams have been left out temporarily to facilitate access to the reactor, but infilling of the remaining members has commenced.

Clean conditioning of the gas ducting, blowers and other plant directly in contact with the circulating cooling gas is necessary if reactor performance is not to suffer. Some of this cleaning is carried out on site, but the majority is performed in the manufacturers' works. Sections of the clean conditioned ducting, parts of the gas circulators and the main gas valves for reactor A are continuing to arrive on site and are being erected. Temporary structures are erected on the tops of the steam-raising unit shells for the installation of the gas circulators and boiler tubing under nuclear clean conditions and two of these are now in use.

During the past few months the first gas circulator drive has been undergoing a test of continuous running under load conditions and under simulated conditions of misalignment, and this has been satisfactorily concluded. More recently, a shock load test has also been successfully carried out. Each gas circulator will be situated in the base of a steam-raising unit so that it will handle gas at the lowest temperature, The circulator will be mounted vertically with the impeller and diffuser inside the shell and the drive outside. This simplifies the gas sealing arrangements.

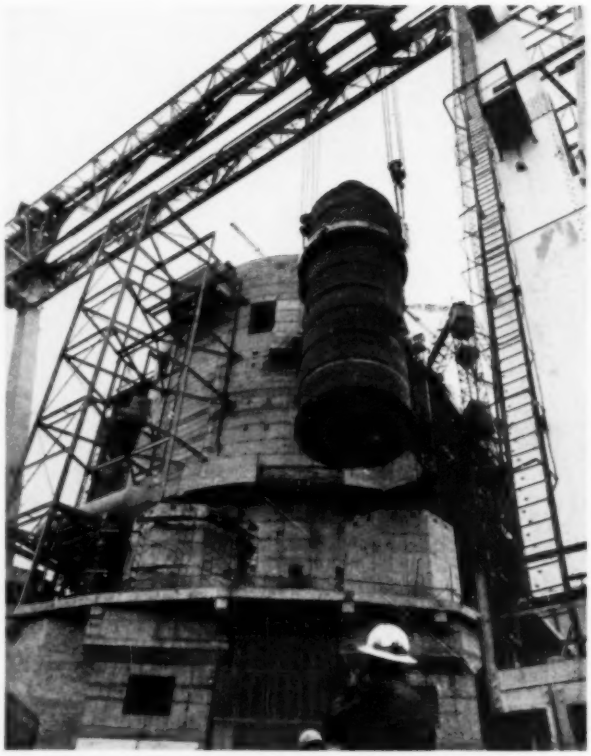


Fig. 3.—The first steam-raising-unit shell being placed on its plinth adjacent to reactor A.

Reactor B.

As indicated earlier the concreting of the 9 ft thick biological shield has reached an advanced state of completion. This has permitted work to proceed on the fitting of the platework on the outer skirt walls and on the inner face of the walls of the biological shield. This platework incorporates full features for expansion and is spaced 2 in. away from the walls to form a region through which air is circulated to control the temperature of the biological shield.

Work on the pressure vessel associated with this reactor is being carried out under cover on the special prefabrication area adjacent to the structure. The outer skirt has been fabricated *in situ* in the reactor vault, while the combined bottom head and support course and the remaining courses were fabricated outside and lifted into position. The gussets to carry the core-support grid have been welded on to the inside of the bottom head, enabling the core-support grid and the next course of the pressure vessel to be lifted from their assembly areas and placed in position.

Although it is not possible to erect the biological shield roof, the two 308 ton members and the six double-webbed T-beams which form the soffit have already been cast and are stacked on the nearby plinths of the steam-raising units.

Steam-Raising Units.

Several steam-raising unit shells have been internally cleaned and are in position on their plinths, and the erection of the main gas ducts and installation of the internal tube banks is proceeding. The shells of the remaining steam-raising units, for both reactors, are

in the process of assembly and are now being produced at the rate of one per month. A number of these have been stress-relieved and tested hydrostatically, and are now being clean conditioned, while more are approaching stress-relief. Further top and bottom head assemblies of the steam-raising units are being fabricated at the works of the manufacturer and are being delivered to site when ready.

Circulating-Water Works.

The construction of this part of the project is probably the most advanced on the station. The intake headwork and jetty are practically complete and the lining of the twin intake tunnels and land shafts is finished: this is also true of the main structure of the pump-house, including the outer stonework facings.

The penstocks and all eight bandscreens inside the pump-house have now been erected, together with the six main circulating-water pumps and their 800 h.p. motors, and associated pipework and valves. The access galleries in the pump-house are also in course of erection.

To prevent fouling of the various culverts and pipework by marine organisms, the circulating-water system is provided with equipment which delivers chlorine solution to the intake headworks. The automatic dosing gear and pumps for this system have been installed in a room in the main pump-house. The drums of chlorine will be kept in a separate storage room, adjacent to the pump-house loading bay, which is fitted with special ventilating equipment to ensure the safety of personnel.

The majority of the civil engineering work associated with the circulating-water culverts, linking the pump-house with turbine hall and the turbine hall to the on-shore culverts on the outfall side, has been carried out. Work on the siphon seal, outfall shafts and on-shore outfall culverts is proceeding while the junctions between the on-shore culverts and the off-shore 10 ft diameter tunnels are practically complete. The construction of the outfall headworks, some 460 yards off-shore, is well up to schedule. The circulating-water system as a whole is due to be tested this summer.

Turbine Hall.

Externally, the turbine hall, with transformers in their stone-filled bays on the north side, presents a finished appearance.

The civil engineering on the interior of the turbine hall is substantially complete. The six turbo-generator foundation blocks are complete and erection of the first set is under way.

Reinforced-concrete blast walls have been constructed to prevent accidental damage to the cabling which will eventually be run over the ' pipe bridge ' linking each reactor to the turbine hall. The tank floor is completed on the south side of the building and all the tanks have been erected and are now being lined internally with protective coatings.

The first four main condensers are installed, and erection of the rest is proceeding. Good progress is reported on the erection of the feed-heating plant and extraction pumps. The access platforms around the first turbo-generator blocks are practically finished and work on those around the next set is under way.

The hydrogen water/water coolers on the north side of the first turbo-generator blocks have now been assembled in position and the copperwork of the first two blocks erected.

The 42 in. inlet and outlet valves in the circulating-water system on the north side of the basement have been fitted and the pipework to No. 1 and 2 turbo-generator sets is finished. The cable racks over the c.w. culverts are ready for receiving the cables, having been extended under the operating floor of the turbine hall.

Under the control room the Mulsifyre-system diesel pumps are installed, together with the refrigerating plant, ductwork, and fans for the central-control-room air conditioning system.

The first of three 1000 kW emergency diesel generators has been erected in the basement of the turbine hall; the remaining two are under constuction. These

Fig. 4.—The top head of the pressure vessel for reactor A suspended from the Goliath crane during positioning inside the reactor vault.

sets will be used to supply the essential power station auxiliaries in the event of a failure of the incoming supply to the station.

The H.P. and L.P. steam receivers have been placed in position and fitted with their valves; in addition, the pipe supports for the steam and feed ranges have been grouted in under the operating floor, and over half of the pipework for the first part of the contract has been erected.

Near the centre of the south annexe, both dump condensers with their desuperheaters have been located, and much of the supporting steelwork is finished. The lift communicating between all floors of the building is ready.

The floors of the switch and battery rooms on the north side of the turbine hall have been completed, and most of the switchgear for the first half of the contract is already in the building.

ANCILLARY BUILDINGS.

The workshop to the east of the turbine hall is nearly complete so far as cladding is concerned, and the crane is already installed. A ' clean conditions workshop ' has been established inside this building and is being used for the final cleaning of the steam-raising units.

The administration building sited to the east of the turbine hall has now been occupied by the staff of the South of Scotland Electricity Board, and the adjoining welfare building is ready for occupation. The nearby uranium and graphite store is complete.

The charge machine maintenance building, to the south of reactor B, is linked to both reactor structures by means of rail tracks. These serve to bring the charge machines, which are at ground level, into the building for servicing.

The building is practically finished, including internal painting, an interesting feature being the inclusion of a clean conditions tower, a necessary adjunct when carrying out maintenance on the interior of the charge machine. A 45 ton crane is installed in the tower for lifting the top off the machine, together with a 25 ton crane in the main hall area. The walls of this building have been constructed from specially fabricated concrete slabs erected inside the main framework so as to present a completely smooth surface for ease of decontamination if necessary. The building will also be equipped with a rehearsal shaft and a complete set of control equipment.

Between the reactors, in the space used initially for prefabricating concrete floor sections, the cartridge cooling pond has been re-excavated and construction is well advanced. This cooling pond is 100 ft long by 75 ft wide by 23 ft deep, the capacity being such that the complete fuel charge of one reactor can be dumped into it in the case of emergency.

Excavation work is proceeding on the foundations of the active-solid-waste building. Much of the associated tunnelling is finished and steady progress is reported on the blinding and asphalting.

The active-waste disposal plant, on the south side of the two reactors, consists of the treatment house, delay tanks, and cartridge-cooling-pond sludge tanks. The delay-tank walls and protective brickwork, and the associated pump-house are well on the way to completion. The walls and asphalt tanking of the sludge tanks have been finished and the brickwork for them is at an advanced stage. Work on the half-completed treatment house is still continuing. Other buildings in varying stages of erection are the decontamination building, the laundry, and feed treatment and filtration buildings.

Fig. 5.—Part of the circulating-water pump-house.

PERMANENT SERVICES.

The sewage treatment plant and the pump-house dealing with the normal foul sewage and storm water from the station are already in operation. Main drainage and water services are also practically finished. Electrical power and control system cabling for the station control room in the turbine hall and the high-voltage cables up to the outgoing switching station are all being laid as required. Good progress is reported in the laying and surfacing of the permanent roads on the site.

Application of Electrical Computing Devices to Mine Winder Problems

By E. FRIEDLANDER, Dr.Ing., M.I.E.E., Engineering Group, Witton.

This paper was first presented to The Institution of Certificated Mechanical and Electrical Engineers of South Africa in May 1960. It gives details of some electrical computers such as control simulators, network analysers and digital computers that can be used for solving mine winder problems. Examples of the types of problems encountered and their method of solution are described to show the advantages and speed of such computing devices. In this abridged version some details of the Witton Network Analyser, which has previously been described in this Journal, have been omitted.

INTRODUCTION.

THE development of science and technology which our present generation is witnessing, if plotted on a scale covering the known history of man, has such a rapidly increasing rise that it is almost like an explosion. This is physically understandable because its present progress is self-propagating. Instead of approaching a stabilized state of saturation which one would have expected a few decades ago on account of the increasing difficulty in any field of activity of a single individual absorbing the rapidly accumulating mass of information, the technical development of gathering, storing, evaluating and redistributing information has far outweighed the restrictions due to the limits of the human brain. The development of electrical computers is a significant element in this process which is gathering momentum at an increasing rate. Forecasting of the consequences of an interplay between a great number of variables, which no one person could ever solve or solve in time to be of any value, is today left to electrical computing devices. These machines are capable of analysing and synthesizing complex problems for which we know the basic relationship but not the synthesis of the complete solution.

The impact of these computing devices on development is so strong that it would be increasingly difficult for any industrial undertaking to keep abreast with contemporary progress without taking full advantage of modern computer techniques where applicable. There are more and more fields of technical work into which the computer now begins to penetrate and to enable problems to be solved or work to be speeded up, thus saving brain- and man-power for more important work.

Problems of winder development are typical examples for which the use of a computer is invaluable. Some of these problems are described in this paper.

GROUPS AND TYPES OF ELECTRICAL COMPUTERS.

There are two different groups of computers. The one may be called 'general computers,' the other 'special computers.' By general computers is meant all those mathematical machines either of the 'analogue' (i.e., continuous metering) or the 'digital' (i.e., bit counting) variety which can serve to solve a great number of different problems. The special computers are more or less simple apparatus adapted to carry out single repetitive calculations or evaluations for one purpose. To the latter group, about which it is not proposed to enlarge in this paper, belong devices such as the returning cam or its equivalent 'the geared potentiometer'[1] which serve to control the deceleration of a winder with correct anticipation of any delays in the control system, or the brake impulse timer[1] which can control the brake application for decking so as to allow for a time interval to reduce decking errors due to brake application delay and varying speed of the winder.

Among the general computers there are three main types to consider:

(*a*) Differential analysers or control simulators which may be either digital or analogue computers.

(*b*) Network analysers which are analogue computers available in several varieties.

(*c*) Digital computers of the well-known class of arithmetical machines capable of solving any problem that can be broken down into more or less elementary steps and which will follow these steps systematically, make logical decisions about the sequence in which steps must be continued, repeated, or alternative routes taken to arrive at the desired solution. Their phenomenal speed of operation and capacity for evaluating a steadily increasing amount of input information are well known.

As it happens, all three of these computers have by now proved to be of value in dealing with problems arising in the field of electrical control and operation of mine winders.

It is proposed to convey some picture of these computers and to give some typical examples of practical applications.

CONTROL SIMULATOR.

Since winder control generally involves some complex dynamic problems which in the past had to be solved by more or less rough approximations, it is obvious that a machine which can tighten the precision of forecasting technical performance and can help the designer to foresee the best dimensions of components for optimum control must be of great value. The difficulties to be met are mainly due to systems involving a considerable number of delay functions, masses to be accelerated, elastic linkages, and non-linearities such as are caused by saturation or other amplitude limitations.

The preferred type of computer for dealing with problems of this kind is an electronic analogue machine, the ' Control Simulator,' based essentially on a suitable inter-connexion of a series of electronic amplifiers[2]. The most important basic elements of this type of computer are:

(*a*) The general purpose amplifier equipped with resistance and capacitance elements which serve as delay function generators, differentiators, and integrators.

(*b*) Signal limiting units representing current limits and saturation effects.

(*c*) General function generators permitting the introduction of more complex non-linear functions other than the signal limiters referred to under (*b*).

Fig. 1(*a*) shows a fundamental element of most control circuits exemplified by the features of a d.c. machine running at constant speed. The machine represents a straight amplifier and, ignoring any non-linearities such as those caused by iron saturation, its static characteristic (fig. 1(*b*)) is a straight line expressing the gain in voltage, current, and power if the circuit constants are known. Dynamically, however, the real ' transfer function ' is more complex due to the delay caused by the magnetic inertia. This leads to an exponential response of the machine output voltage to the exciter input voltage if the exciter voltage is applied by a switching process in the field circuit, with a time delay corresponding to the magnetic time constant T of the machine as shown in fig. 1(*c*). A transfer behaviour of this kind is usually represented by the simple block symbol (fig. 1(*d*)).

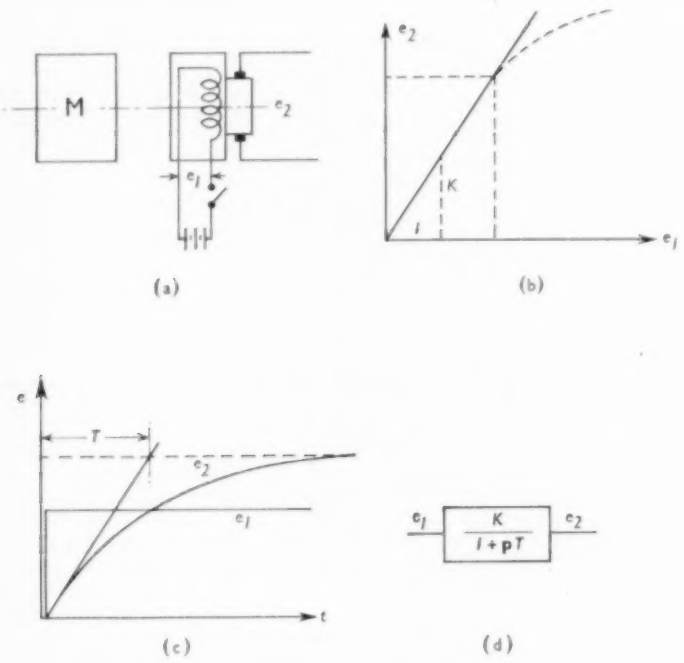


Fig. 1.—A d.c. generator as an example for a single delayed control unit.

Most circuit elements of a complex control system can be introduced in a similar way. In addition there are delays due to masses to be accelerated, stabilizing feedbacks picking up rates of change of system variables, elasticity, and many other features which must be represented. The electronic amplifier is a most versatile tool to simulate the transfer functions of practical control stages of this and other kinds.

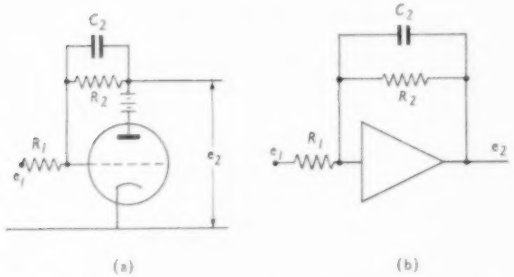


Fig. 2.—Representation of a delayed control unit by a valve amplifier.

Fig. 2 shows how the simple delay function of the d.c. machine is represented in the electronic amplifier circuit. It may be assumed that the valve amplifier shown in circuit (*a*) of fig. 2 has so much gain that even a minute positive grid voltage would drive it into an overload condition. Consequently the grid potential must in practice always be kept near to cathode potential (i.e., at zero). This is achieved by the negative feedback from the output voltage. The grid current can be assumed to be negligibly small. Application of the elementary laws of electric circuitry then yields directly the relationship between the control voltage e_1 and the output voltage e_2, i.e., the transfer function from

$$e_1 \cdot \frac{1}{R} - e_2 \cdot \left(\frac{1}{R_2} + \mathbf{p}C_2\right) = 0 \qquad \text{.....(1)}$$

control input current — output feedback current — grid current

The letter **p** is taken as an abbreviation for the differentiating process involved so that, for instance, $e_2\mathbf{p}C_2 = C_2\frac{de_2}{dt}$ is the charging current taken by the capacitor C_2 when the voltage e_2 undergoes a change. Equation 1 gives with the introduction of $R_2\,C_2 = T$ (the time constant of the feedback loop) the transfer function:

$$\frac{e_2}{e_1} = \frac{R_2}{R_1} \cdot \frac{1}{(1+\mathbf{p}T)} \qquad \text{.....(2)}$$

which satisfies the same basic relationship as that shown in fig. 1 for the simple d.c. machine. $\frac{R_2}{R_1} = K$ represents the gain or static characteristic as in fig. 1(*b*) and T is the time delay by which e_2 follows any step variation of e_1. Fig. 2(*b*) is the accepted symbol for an amplifier representing the transfer function which corresponds to the block diagram symbol of fig. 1(*d*).

There are many different circuits available to represent the various interrelations experienced in practice. If the capacitor C_2 is omitted an ordinary undelayed amplifier of gain $\frac{R_2}{R_1}$ is obtained. If R_2 is made infinite the resulting relationship $\frac{e_2}{e_1} = \frac{1}{\mathbf{p}R_1C_2}$ indicates an integrating process since $R_1C_2 = \frac{de_2}{dt} = e_1$ and therefore

$$e_2 = \frac{1}{R_1C_2}\int_{t_0}^{t} e_1\,dt \qquad \text{and so on.}$$

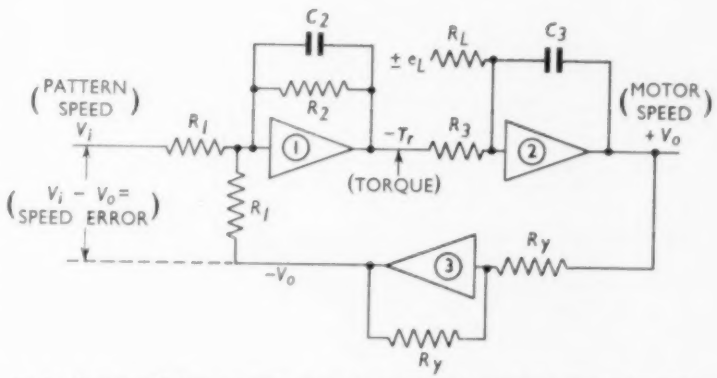


Fig. 3.—Over-simplified representation of an a.c. winder speed control by a control simulator.

In this way the electronic simulator not only portrays the relationships between voltages of a given system, but can also portray voltages, currents, torque, and speed by voltages in correspondingly interconnected amplifier stages.

Fig. 3 shows an over-simplified circuit of a speed-controlled a.c. winder motor. The basic elements consist of a pattern-speed generator representing the input speed signal and a tachogenerator representing the output speed signal. The difference between these speed signals fed into the torque control amplifier produces the motor torque. The over-simplification introduced here in order to make this example easy to understand is that we visualize the control of the motor current to follow the torque signal with a simple

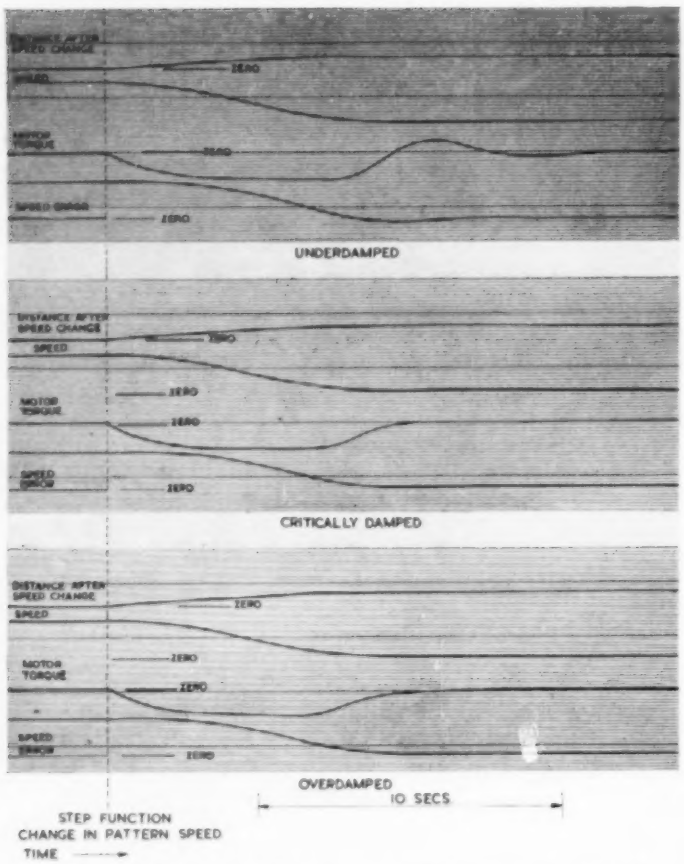


Fig. 4.—Recordings of the speed response to pattern-speed signal switching for different conditions of tuning.

exponential time delay T_1. (Torque limitation is neglected.) To the output of the first amplifier stage is then added or subtracted a current representing the static load and the resulting out-of-balance torque, i.e., the accelerating torque is integrated in the second amplifier stage. This integration gives the actual motor speed from which the initial speed error or torque signal had been derived by comparison with the pattern speed. A polarity reversing amplifier must be interposed in this case before the loop is closed.

The circuit to represent an actual winder is more complex of course. The problem and particularly the requirements for stabilization are derived from a correspondingly expanded circuit which may represent such intermediate quantities as rotor current, liquid controller position, non-linearity of the controller characteristic, rate of change of speed, and so on.

Fig. 4 gives an example of how the optimum choice of feedback stabilization may be determined experimentally and is shown in the recordings taken from the simulator. Investigations of this kind are the main general field of application for control simulators.

A particularly interesting problem arises in the winder field from the requirements of making a modern winder, and particularly an a.c. winder with its inherent limitations of response, satisfy the conditions for automatic operation. This is to make

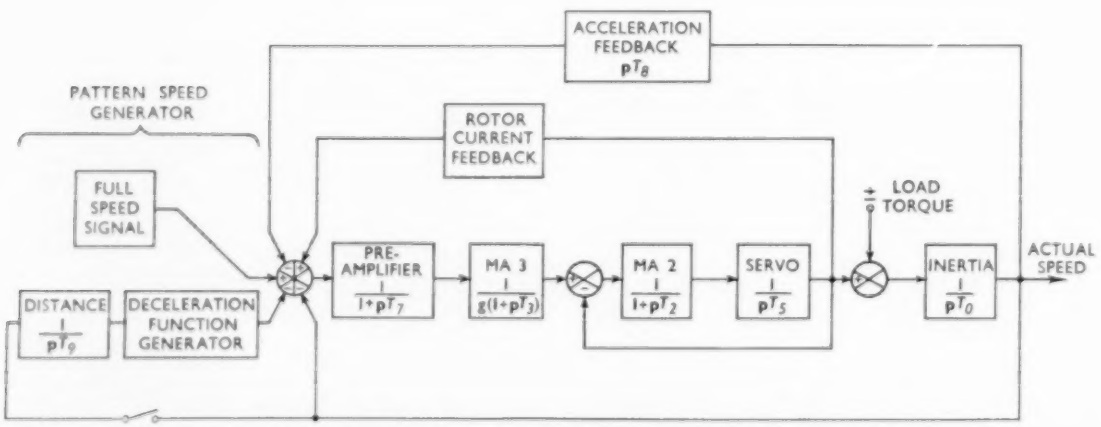


Fig. 5.—Block diagram for simulator tests on automatic deceleration control of a low-regulation winder.

the winder respond to a suitable pattern-speed controller in such a way that the winder can complete the wind with a minimum loss of time in spite of inherent time delays. We must learn to do automatically what a skilled driver would be able to do by suitable anticipation of all delay effects. We must find out how the pattern-speed voltage distribution, such as is obtained from a returning cam or a geared potentiometer, should be best distributed over the distance of the wind. It is of particular interest to check how a winder having a rather complex response behaves in its approach to the end of the wind under differing conditions of load, and how accurately it can approach the ideal winding cycle within the limits imposed by practical features of a given control system. In problems of this kind the control simulator can be of great help.

Fig. 5 shows the block diagram of an a.c. winder equipped with special feedbacks for low regulation and artificial stabilization to which have been added the features of the returning cam whose actual shape is left open to experiment. The basic (uncompensated) gain $K=\frac{1}{g}$ is expressed in this block diagram by the 'regulation' g of amplifier $MA3$.

The returning cam is introduced by deriving first a function representing the distance travelled in the shaft by simple integration of the speed signal: this distance is then transformed into a speed pattern signal by means of an adjustable non-linear function generator. This relationship actually represents the shape of the returning cam. It is now possible to experiment with it in the laboratory and to determine

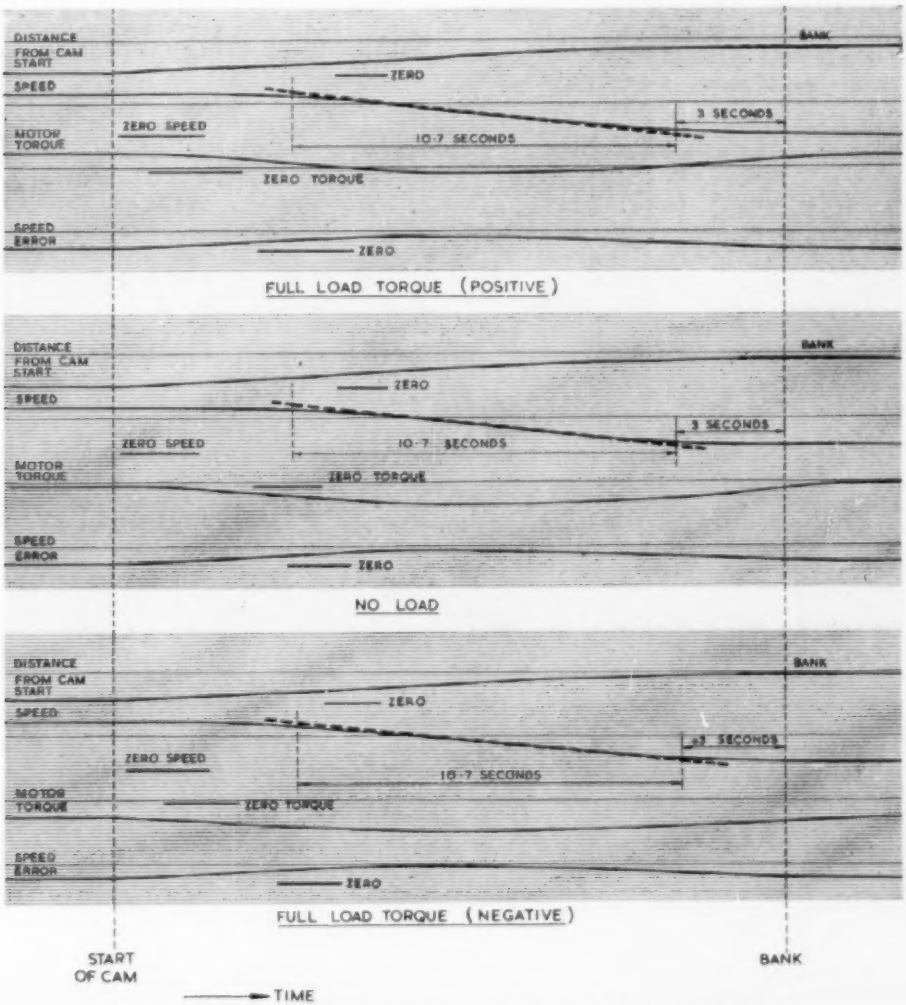


Fig. 6. Deceleration control of a low-regulation winder under different conditions of load.

the actual shape of cams necessary before the equipment is erected. Fig. 6 shows an example of one experiment of this kind in which, however, the shape of the returning cam was not perfect. Work on this subject is still in progress. It is seen that even with this rough first shaping of a pattern speed function it is possible to obtain a winding cycle in which the bank is approached with an identical speed pattern over the last half turn or so irrespective of the load. This is important if prolonged creeping is to be avoided under all conditions. The recordings reproduced in fig. 6 show that the loss of time for tailing-in at the ultimate creep speed did not exceed three seconds in the three extreme cases of load which had been compared with each other, although a rather sluggish response of the winder control had been assumed.

It should be stressed, however, that this refers only to an a.c. winder controlled through a large liquid controller and that the pattern would be different for a modern grid-resistor control of an a.c. winder, as will be explained elsewhere, or for a quick - response d.c. winder, particularly if supplied from a rectifier.

The control simulator used for these experiments is shown in fig. 7.

NETWORK ANALYSER.

Great care is necessary if the supply for large winders is taken from town networks not connected to large grid systems because of the reaction that the fluctuating power consumption can have on the voltage of the supply system. This applies particularly to rectifier installations which may also call for special attention to the effect of harmonics.

Problems of this kind are of course well known and methods of calculation are available. However, modern systems are becoming so complex that it is hardly possible for a planning engineer to foresee all the effects of the fluctuating and distorted load currents on the supply system to which the winder is connected without spending more time on this work than is justified.

Any network analyser will be suitable for this work. However, the G.E.C. decided for a number of technical reasons to install the rather unusual and less well-known transformer type of network analyser, a full description of which was published in the *G.E.C. Journal*, Vol. 25, No. 4, October 1958. It will be recalled that this analyser was developed by Blackburn from the straight transformer analyser invented by Mallock[3], in which Ohm's Law, i.e., the proportionality between voltage and current, was represented by a transformer with an adjustable turns ratio. Blackburn expanded this principle to cover the relationships in a complex a.c. system by replacing the variable ratio transformer with an impedance unit of the type shown in fig. 8.

It is believed that this analyser is the most accurate calculating unit of its kind available in the United Kingdom and some problems have already been solved with it for which the conventional analyser has proved to be inadequate. It would of course exceed the limits of this brief report to mention all details of facilities which in practice are open to the operator. A fuller description will be found in ref. [4,5].

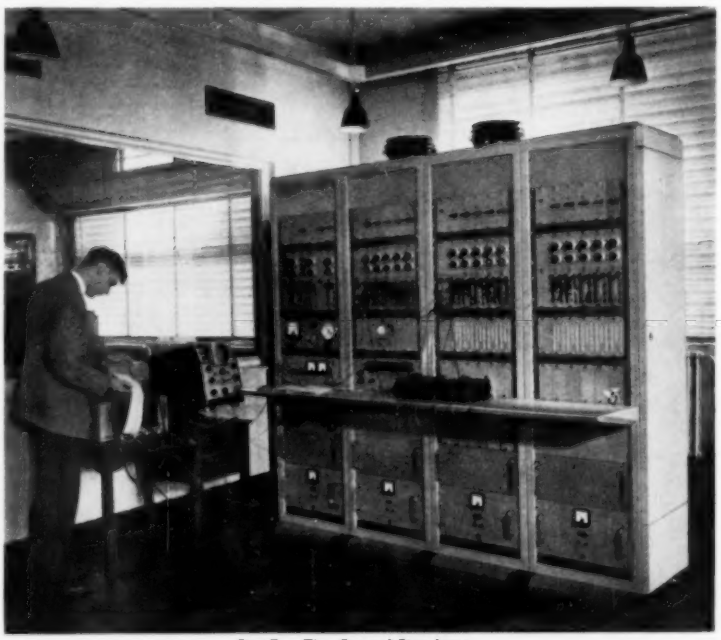
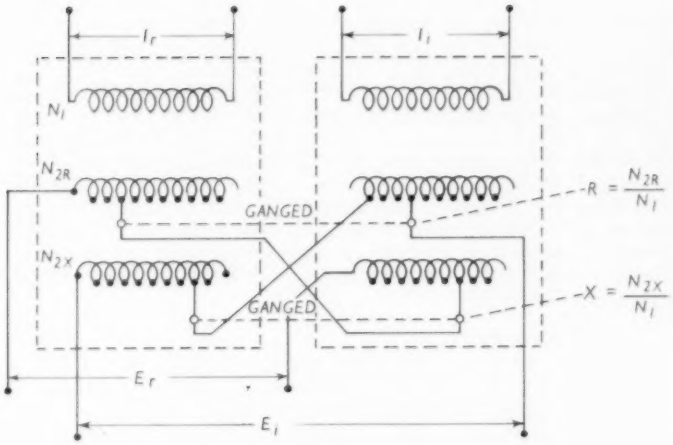


Fig. 7.—The Control Simulator.

FEATURES OF THE WITTON NETWORK ANALYSER.

The complete analyser is shown in fig. 10. The setting up of a complex network, which is necessary for any of the investigations of the kind required, is made in a similar way to that which is usual for the conventional type of network analyser. The individual units can be connected with each other in series or in parallel by means of a plug-board. The four sections of the units as well as the plug-boards are clearly recognizable. Busbars are provided for parallel connexions. These are automatically achieved by placing plugs side by side along a given bar. It is only necessary to use certain ' terminating ' plugs to complete the circuit of



$$E_r = I_r R - I_i X$$
$$E_i = I_i R + I_r X$$

Fig. 8.—Blackburn impedance unit for a transformer type a.c. Network Analyser.

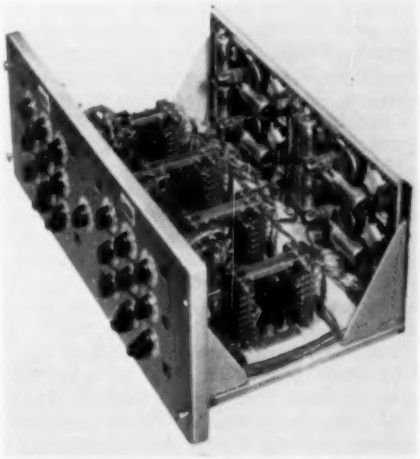


Fig. 9.—One double unit of the Network Analyser.

Fig. 10.—The Witton Network Analyser.

a number of units connected in parallel. This is the only point in which the principle of normal network plugging of the analyser for ordinary network calculation differs from the scheme usual with conventional analysers. In addition, special front panel connexions are possible for certain mathematical operations such as matrix calculation and phase sequence analysis[5].

Most important, of course, is the reading of the results. The metering desk shown in the centre provides two metering units, one using conventional instruments, the other using self-balancing bridges to give the results in complex component numbers directly in digital form. All instruments read voltages or products of voltages. Suitable scales then allow readings to be made in volts, amperes, kW and so on.

The analyser can be used in two groups or can be linked together into one large unit, depending on the type of problem to be investigated. When the analyser is split into two units, one operator will use the scale instruments, the other the digital metering equipment.

Applications of the Network Analyser in the Winder Field.

Voltage drop and voltage fluctuation.

The human eye is rather sensitive to variations of illumination due to changes in the system voltage particularly if these variations are periodic. Fortunately enough the worst flicker frequencies are about five to eight cycles per second and they are sufficiently far below the frequencies encountered in winding cycles that no attention need be given to them here. The permissible voltage dips due to starting of winder motors will still be in the order of only a few per cent particularly when supplied from the distribution system of large towns or under other special conditions. The problem that arises here is one of predetermining accurately a variation of the r.m.s. network voltage due to superimposed load currents of varying phase angle. It is not possible to measure the actual voltage change on a network analyser with the necessary accuracy unless the analyser and its metering equipment are precise. The transformer analyser scores on this count for the reasons given above.

However, a more satisfactory method is to calculate or measure directly the actual change of r.m.s. voltage at any important point in the network. The easiest approximation for a calculation of this kind is known to be given by

$$\Delta E = R_n I\cos\phi + X_n I\sin\phi$$

where ΔE is the actual voltage drop
$I\cos\phi = I_{rl}$ the real component of the load current and $I\sin\phi = -I_{il}$ it simaginary or wattless component. The negative sign is due to the convention that a positive I_i means a leading current but a positive phase angle ϕ a lagging current.

R_n and X_n are the complex components of the network impedance Z_n seen from the point at which the load current is taken or where the effect of a branch of this current, encountered in the network, must be studied. R_n and X_n are obtained on the transformer analyser in the same way as on any conventional analyser by making all input voltages zero at the points where the voltage may in practice be assumed to be held rigidly constant. If the load current is injected into the network at the point of interest in the usual way, measurement of voltages E_r and E_i give the in-phase and quadrature component of the voltage-drop vector. Thus the analyser measures directly the important quantity ΔE with great accuracy and without intermediate evaluation of R_n and X_n.

When the voltage fluctuation for the system has been measured, the study is often continued to determine the rating and location of suitable flicker-reduction equipment.

Harmonics

The wave distortion caused by rectifiers is only rarely of any significance. In many networks nowadays rectifiers with ratings much larger than the power requirements for single winders, are encountered. If adequate attention is given to critical supply conditions and if the number of phases is chosen correctly to exclude such critical conditions there is no objection to the use of rectifiers. However certain configurations do want attention. Quite appreciable wave distortions have been found due to conditions of resonance and in particular cable networks fed from transformers whose kVA rating is insufficiently above the capacitive power of the cable can be troublesome. Similarly, large units of power-factor correcting capacitors fed through relatively small transformers can produce resonance effects with consequent unexpected distribution of the harmonic current over a given network, leading possibly to overloading of individual components. This, for instance, may apply to installations connected to the same busbar within a given mining installation where power-factor correcting capacitors are used in conjunction with motors or other underground equipment.

As it is the distribution of the harmonic currents over the network and their possible concentration into single branches due to resonance absorption that must be watched, a network analyser permitting the injection of these harmonic currents and the study of their course through the maze of a normal system can be invaluable.

If as a precaution the use of absorption filters for the most important harmonics is decided on, there may still be problems connected with the best distribution of the filter components themselves. The example given in fig. 11 refers to an unusual but nevertheless interesting condition encountered in connexion with efforts to suppress the harmonics in a system involving an arc furnace and a current limiting reactor. The diagram gives the complete distribution of harmonic voltages occurring with currents of any frequency and with current amplitudes which decrease reciprocally with the frequency. This applies, for instance, to the harmonics in a rectangular wave. An arc furnace is capable of producing odd as well as even harmonics due to its inherent and unavoidable asymmetries.

The diagram, which shows the complete spectrum of voltages that could occur if all frequencies were pos-

sible, indicates clearly the importance of suppressing not only the odd but also the even harmonics. As there is always a large voltage amplitude possible between adjacent filters, the application of only the third, fifth, and seventh harmonic filters would have given an opportunity for the second harmonic to develop unduly.

This frequency range is, of course, not of any interest in rectifier drives where rarely less than twelve anodes will be chosen so that the eleventh and thirteenth harmonics are usually the lowest to be expected, provided that the network is not infested with lower harmonics before the rectifiers are added.

Studies of this kind show the help that may be expected for future installations particularly where d.c. winders supplied from grid-controlled rectifiers are under consideration.

DIGITAL COMPUTER.

One of the first of the investigations that has to be made on the electrical side when a winder project is under consideration is the shape of the winding cycle diagram (fig. 12) which will give the least expensive motor. This means that the acceleration and deceleration periods and the maximum rope velocity can still be varied even when the shaft output, pay load, rope weight, inertia of the mechanical system, drum or pulley diameter, and so on, are already fixed. It may sometimes pay to probe into the choice of some of the basic data such as the payload or the out-of-balance rope weight.

$$e_n = \frac{I}{n} \cdot Z_n$$

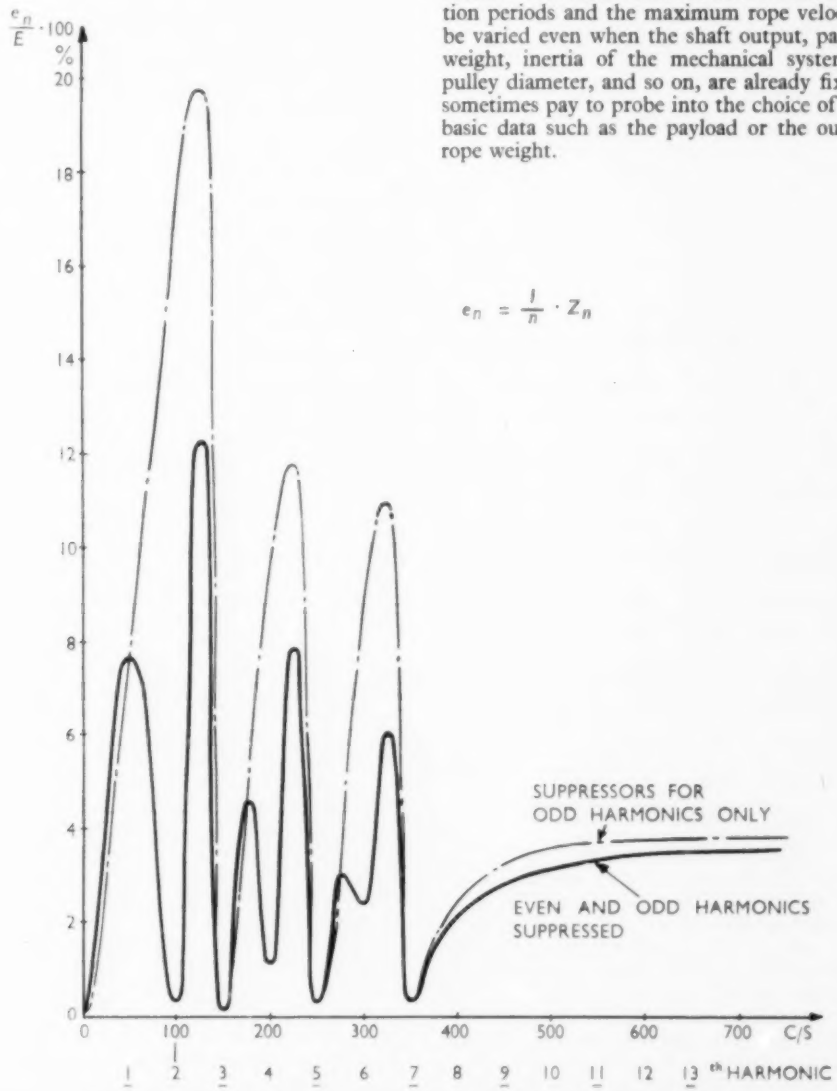


Fig. 11.—Example of an harmonic response analysis on the Witton Network Analyser.

TABLE 1.

DATA TO BE GIVEN TO COMPUTER FOR WINDER CALCULATION.

WINDER No. *522/2* (including duty reference).

A = *230* ton/hour (output)

B = *8·87* tons (out of balance load) { positive for raising load, negative for lowering load

kB = *10·47* tons (load including friction)

$T4$ = *10* sec (decking time)

s = *5600* ft (shaft depth)

I = *184 000* lb ft/sec² (inertia without motor)

R = *4·87* ft (average radius of rope coiling)

w = *4·35* lb/ft (out of balance rope weight—including coiling effect)

h = *0·98* 1/1 (Gear efficiency co-efficient—reciprocal for lowering load)

Calculations using first:

m = $\frac{585 \text{ lb ft}}{\text{h.p.}}$ (motor inertia factor)

c = 1 (deceleration time factor)

(Figures (*in italics*) correspond to data tape of Table 2.)

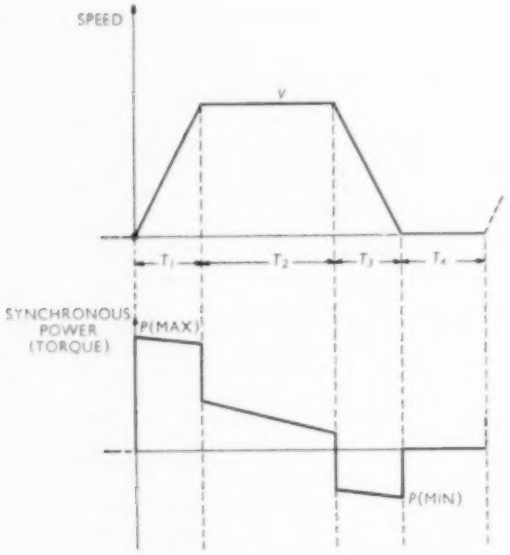


Fig. 12.—Winding cycle definitions.

The more variables that are left open and the more different load conditions that must be studied, the more cumbersome is the work to be done. The time which has been required for calculations of this kind in the past has frequently been too great for the limited manpower available to cope with all enquiries.

Because the same kind of calculation must be repeated time after time using different numerical data in each case, it is clear that great benefits can be derived from a digital computer. This has led to the following procedure:

The information which the design or estimating engineer must pass on to the computer department is contained in a simple form such as shown in Table 1, which is self-explanatory. These data are derived from the specification and from information provided by the mechanical departments concerned with the shaft equipment. R is of course the effective radius of the drum and the layers of rope with single or multi-layer coiling.

The 'out-of-balance rope weight' w takes into account the effect of any balance rope. By a fair approximation, w is used to introduce at the same time the variation of the out-of-balance load due to multi-layer rope coiling during the wind because this variation is similar in character to that due to an unbalanced rope even though this variation takes place in steps. For a winder with single layer coiling and a balance rope equal in weight to the carrying rope, $w=0$.

The factor $m = \frac{I_m}{P_{max}} \cdot \frac{V^2}{R^2}$ introduces the motor inertia with reference to the peak horsepower P_{max} of the motor as a first approximation from experience. The choice of m is checked when the nearest possible motor size has been found and the calculation is repeated if necessary with a new value of m once the actual motor inertia I_m can be assessed.

The coefficient $c = \frac{T_1+T_3}{2T_1}$ introduces any choice of deceleration period T_3 different from the acceleration period T_1. With $T_3=T_1$, $c=1$ but c can be varied if the relationship between P_{max} and $-P_{min}$ obtained indicates that any advantage may be derived from a deviation from this choice.

In addition to the data input (the information contained in Table 1), the computer must receive a programme input which contains all the algebraic calculations necessary and all instructions as to the results required. This is written in the special code of the given computer. With the use of a modern auto-code system such as applies to the Ferranti Mercury Computer, it is no longer necessary to break down the whole process of calculations into the last details. This is done automatically by the computer and the input information actually contains the mathematical steps and symbols in a relatively simple form.

The mathematical symbols, steps, and numerical data required are fed to the computer by means of a paper tape which is perforated by a teleprinter, all necessary characters being represented by a suitable code. The auto-code programme is stored permanently on a perforated tape and only the data tape has to be prepared anew for each case.

The results from the computer are obtained on another perforated tape. They show the maximum rope velocity V, the maximum horsepower P_{max} (referred to maximum speed), the r.m.s. horsepower over the complete winding cycle, the minimum horsepower P_{min} (maximum negative horsepower for braking) and the ratio of $\frac{P_{max}}{P_{rms}}$ all given as a function of the chosen

Digital Computer Calculation of Optimum Winding Cycle.

Autocode Programme Tape

```
TITLE
WINDERS ESTIMATION CALCULATION CS D33/MA56
TITLE
   T1    V    P(MAX)    P(RMS)    P(MIN)    RATIO
CHAPTER 1
A->50
Y->50
π->50
1)READ(R)
N=11R+10
I=0(1)N
READ(A1)
REPEAT
JUMP 8, R=1
A2=A1A2
8)I=0(1)R
N=11I
πI=3600A(N+1)/AN-A(N+3)
π(I+2)=4·0727273A(N+2)
π(I+4)=-DIVIDE(A(N+5), 550A(N+6)A(N+6))
A(N+9)=A(N+9)/550
π(I+6)=π(I+2)+A(N+7)A(N+4)/550
π(I+8)=2A(N+10)-1
REPEAT
I=10(1)40
X=·51
Z=0
J=0(1)R
N=11J
NEWLINE
JUMP2, J=0
K=1(1)7
620, 14
REPEAT
JUMP3
2(PRINT(X)2, 1
3)V=-DIVIDE(A(N+4), πJ-A(N+10)X)
PRINT(V)2, 1
YJ=-DIVIDE(π(J+6)VX+π(J+4)VV, X-A(N+9))
JUMP7, 0>YJ
PRINT(YJ/A(N+8))5, 0
Y(J+2)=YJ-·00181818A(N+7)VVX
G=πJ-2A(N+10)X
Y=·0018181818A(N+7)VVG
Y(J+4)=π(J+2)V+Y
Y(J+6)=π(J+2)V-Y
Y=-DIVIDE(Y(J+2)-Y(J+4), π(J+8))
Y(J+8)=Y(J+6)-Y
Y(J+10)=Y(J+8)-·0018181818A(N+7)VVXπ(J+8)
A=YJYJ+YJY(J+2)+Y(J+2)Y(J+2)
B=Y(J+4)Y(J+4)+Y(J+4)Y(J+6)+Y(J+6)Y(J+6)
C=Y(J+8)Y(J+8)+Y(J+8)Y(J+10)+Y(J+10)Y(J+10)
D=-DIVIDE(AX+BG+Cπ(J+8)X, 3πJ-2A(N+10)X+A(N+3))
Z=Z+D
JUMP4, J=R
Z=-DIVIDE(Z, R+1)
Z=-SQRT(Z)
PRINT(Z/A(N+8))5, 0
JUMP5
4)K=1(1)8
620, 14
REPEAT
5)PRINT(Y(J+10)/A(N+8))5, 0
JUMP6, J=R
PRINT(YJ/Z)1, 3
6)REPEAT
620, 13
REPEAT
7)RMP
XSQRT
CLOSE
```

Data Tape

```
TITLE
WINDER NO. 522/2.    JOB NO. 50—11/2/60
CHAPTER 0
ACROSS 1/1
CLOSE
0
230  8·87  10·4666  10  5600  184·000  4·87  4·35  ·98  585  1
```

Output

```
WINDERS ESTIMATION
CALCULATION CS D33/MA56
WINDER NO. 522/2
JOB NO. 50—11/2/60
```

T1	V	P(MAX)	P(RMS)	P(MIN)	RATIO
5·0	45·2	12572	3703	−8638	3·395
5·5	45·4	11681	3616	−7731	3·231
6·0	45·6	10975	3550	−7009	3·091
6·5	45·8	10402	3501	−6420	2·971
7·0	46·0	9930	3463	−5931	2·867
7·5	46·2	9534	3434	−5518	2·776
8·0	46·3	9198	3412	−5166	2·695
8·5	46·5	8910	3396	−4861	2·623
9·0	46·7	8661	3385	−4595	2·559
9·5	46·9	8444	3377	−4362	2·501
10·0	47·1	8254	3372	−4154	2·448
10·5	47·3	8086	**3370**	−3969	2·399
11·0	47·5	7938	3371	−3804	2·355
11·5	47·7	7806	3373	−3654	2·314
12·0	47·9	7688	3377	−3518	2·277
12·5	48·1	7583	3383	−3395	2·242
13·0	48·3	7488	3390	−3282	2·209
13·5	48·6	7403	3398	−3179	2·179
14·0	48·8	7327	3407	−3084	2·151
14·5	49·0	7258	3417	−2997	2·124
15·0	49·2	7196	3428	−2916	2·099
15·5	49·4	7140	3440	−2841	2·075
16·0	49·6	7089	3453	−2771	2·053
16·5	49·9	7043	3466	−2707	2·032
17·0	50·1	7002	3481	−2646	2·012
17·5	50·3	6965	3495	−2590	**1·993**
18·0	50·5	6932	3510	−2537	1·975
18·5	50·8	6903	3526	−2487	1·957
19·0	51·0	6876	3543	−2441	1·941
19·5	51·2	6853	3559	−2397	1·925
20·0	51·5	6832	3577	−2356	1·910

acceleration period T_1 which is varied from 5 to 20 seconds in $\frac{1}{2}$ second steps. Table 2 shows the printed contents of the data tape and of the output tape for the numerical data given in Table 1.

Similar output information is obtained for the various conditions of load that may be specified. A comparison of requirements enables the designer almost at a glance to choose the best winding cycle which will satisfy all conditions involved and which will require the least expensive driving motor. As is well known this choice may be influenced in one case by the lowest r.m.s. horsepower value of the motor, in another case by the ratio of peak horsepower to r.m.s. horsepower required. Two typical points of interest are marked in Table 2. The one shows the minimum r.m.s. value, the other the condition $P_{max} = 2P_{rms}$.

Obviously this saves a great amount of cumbersome and time-consuming calculation, even if the final choice is checked by the usual long-hand slide-rule calculation as a safeguard against any errors in the machine work.

The practical sequence of steps consists of first preparing, perforating, and testing the general programme tape. Once this is available only the short data tapes need be perforated whenever a new calculation is required. The tapes are perforated on the special teleprinter-type machine shown in fig. 13.

Fig. 13.—Teleprinter tape punching and printing machine.

CONCLUSION.

The present survey of examples in the winder field indicates clearly the typical range of problems for which each one of the three general computers discussed are most suitable.

The control simulator deals most easily with individual 'one off' problems involving mathematically difficult equations and has the great advantage of permitting the operating engineer to observe the performance of each component in a complex structure such as the transient performance of a control mechanism. It therefore keeps the intuitive reaction of the designer more alive.

The network analyser serves mainly to obtain a survey of mass results wanted in an essentially linear but usually complex system. It is predominantly, but far from exclusively, an a.c. circuit calculator.

The digital computer on the other hand is a most versatile tool, eminently suitable for difficult repetitive calculations and, beyond this, but at the moment outside the winder field, for the solution of mathematical problems some of which, without its enormous speed of operation, could never be completed by long-hand in the lifetime of any one person.

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Electrical Equipment for a Floating Crane

By J. G. F. DERRINGTON, A.M.I.E.E. Engineering Group, Witton.

THE Mersey Docks and Harbour Board owns and controls docks at Liverpool and Birkenhead extending for about seven miles on the Lancashire side of the River Mersey and four miles on the Cheshire side of the river. The dock estate covers more than 2000 acres, and there are some thirty-seven miles of quays. The geographical position of the Port of Liverpool makes it the natural outlet for exports from the industrial North and Midlands, which include heavy engineering products such as transformers, alternators and locomotives demanding lifting capacities beyond the range of quay-side cranes or ship's derricks.

At Liverpool it has been the accepted practice for nearly eighty years to take the 'lift' to the ship, and because of the extensive area of the dock system the floating cranes used for this purpose must be capable of transporting the loads from quay to ship and must also be self-propelled to avoid the expense of employing tugs. The Board today maintains under its control a fleet of seven self-propelled floating cranes which collectively deal with some 4000 tons of heavy-lifts each week, as well as providing facilities for port maintenance.

Fig. 1.—60 ton diesel-electric floating crane 'Samson'.

The latest addition to this fleet is the diesel-electric

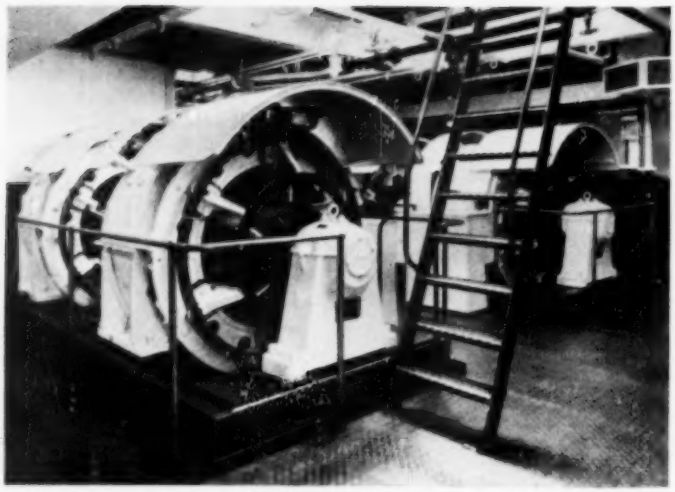

Fig. 2.—Main and auxiliary generators.

floating crane 'Samson' (fig. 1) which was built by Simons-Lobnitz Ltd. of Renfrew, Scotland. The vessel has been designed specifically to meet the difficult conditions prevailing at the Port of Liverpool, which demand a relatively high speed of 10½ knots to cope with the tidal currents prevailing in the main channel, together with maximum manoeuvrability for satisfactory operation in confined areas.

'Samson' has an overall length of 183 ft and a moulded breadth of 56 ft, and is equipped with G.E.C. main electric power and propulsion equipment which was supplied to the order of Charters of Glasgow acting on behalf of the shipbuilders. She is powered by Paxman diesel engines and the structural and mechanical parts of the crane were supplied by Cowans Sheldon & Co. Ltd.

To ensure maximum manoeuvrability and to offset the large windage area of the main structure, the specially shaped hull is equipped with widely spaced twin screws and rudders together with a transverse bow manoeuvring jet. This jet comprises a 200 b.h.p. motor-driven axial-flow pump mounted in a transverse duct in the bows with outlets on the port and starboard sides of the ship. The device is capable of exerting a lateral thrust of 2 tons in either direction and has proved to be of considerable value when manoeuvring at slow speeds in confined waterways.

The main hoist of the crane has a capacity of 60 tons at a speed of 15 ft/min over a radius ranging from 78 ft 8 in. max. to 15 ft min, and can be slewed through 360° with a 60 ton load in four minutes. The auxiliary hoist has a capacity of 25 tons at a speed of 55 ft/min over a maximum radius of 93 ft 8 in. A power-driven travelling ballast weight is used to counterbalance the load being lifted.

POWER EQUIPMENT.

Each of the two 900 h.p. 600 rev/min Paxman 12 YLXZ diesel engines is connected through a flexible coupling to a main and an auxiliary generator (fig. 2). The rating of each main d.c. generator is 330 kW at 440 V and of each auxiliary d.c. generator 300 kW at 220 V. Power for the propulsion motors is obtained from the main generators, and for all other services from the auxiliary machines. The rating of the auxiliary generators is such that one machine is capable of supplying the entire crane and auxiliary service loads. A further two 30 kW 220 V d.c. generators, each driven by a Ruston 6YCZ diesel engine, provide power for the essential services when the 300 kW auxiliary generators are not running. Paralleling of all the 220 V generators is possible, thus preventing interruption of these services when changing the source of supply.

PROPULSION MOTORS.

The screws are direct-coupled to 400 h.p. motors (fig. 3) which are mechanically and electrically independent, separate Ward Leonard speed-control systems being employed for each motor. Four steps of speed in either direction are provided for each motor by varying the excitation of the appropriate generator field.

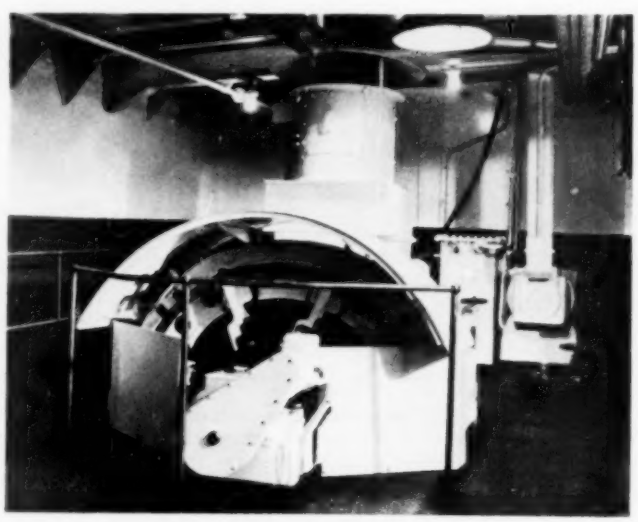

Fig. 3.—400 h.p. starboard propeller motor.

Relays automatically reduce this excitation if attempts are made to increase the load on the propulsion motors too rapidly, and remove the excitation completely under conditions of sustained overload.

Control of motor speed is normally exercised from the bridge, where there are three double-telegraphs mechanically linked through clutches to the operating shafts of the control cubicles. The propulsion motors can also be operated from the engine room by hand-wheels mounted on the control desk (fig. 4.)

An alarm indication panel located between the motor control cubicles is arranged to give warning should a fault occur on selected parts of the propulsion equipment. In such circumstances the appropriate green light is extinguished, and a red panel indicating the type and position of the fault is illuminated. An audible alarm is also sounded; this can be silenced by pressing a switch, but the red panel remains illuminated until the fault has been rectified.

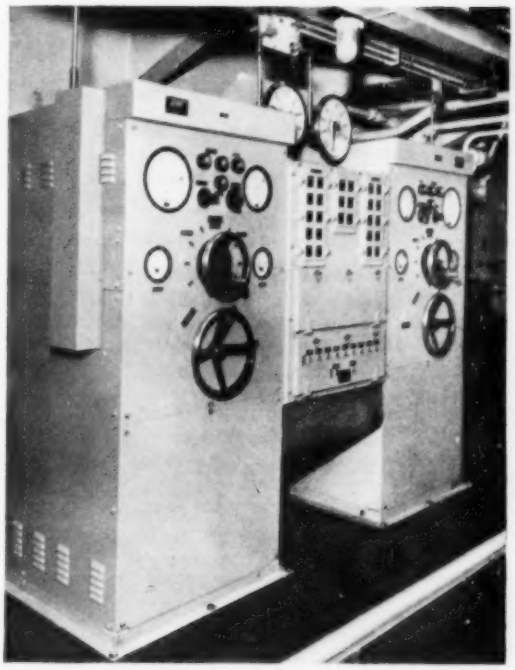

Fig. 4.—Control desk for the propulsion motors.

HOISTING AND DERRICK MOTORS.

Power for the 130 h.p. crane hoists and the 75 h.p. derrick motor is obtained from a 107 kW Ward Leonard set, which in turn is supplied from the 220V auxiliary generator system. A 3-position rotary selector switch enables a choice of either of the hoists or the derrick motor to be made, the speed of the particular motor selected being controlled by a 9-notch controller of the lever type. Speed control is effected by varying the separately excited and self-excited fields of the Ward Leonard generator, with the additional facility, in the case of the crane hoist motors, of field weakening on notch 9. The circuit is so arranged that in the event

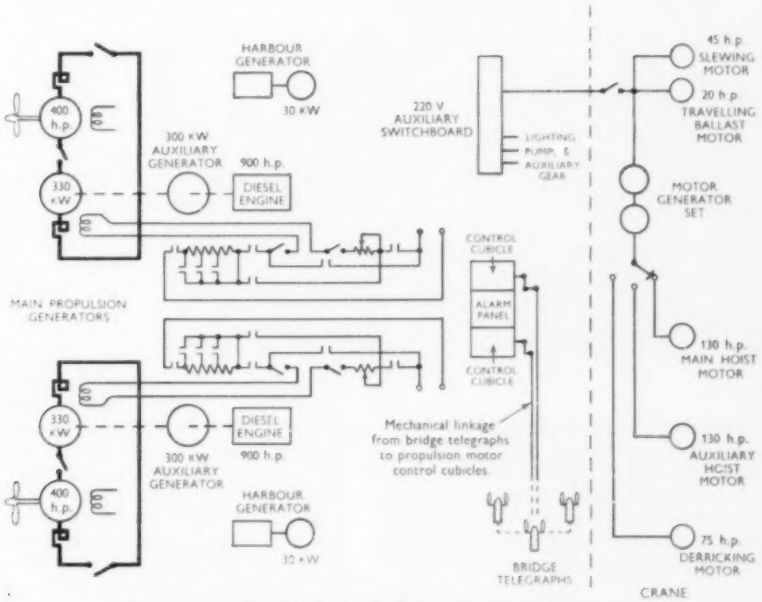

Fig. 5.—Simplified schematic diagram of main control circuits.

of an overload, or the tripping of a limit switch, the controller has to be returned to the first notch before the particular motor can be re-energized. When loads are being lowered, regenerative braking is employed, and if the auxiliary system is incapable of absorbing the regenerated power, ballast resistors are automatically introduced into the circuit to assist.

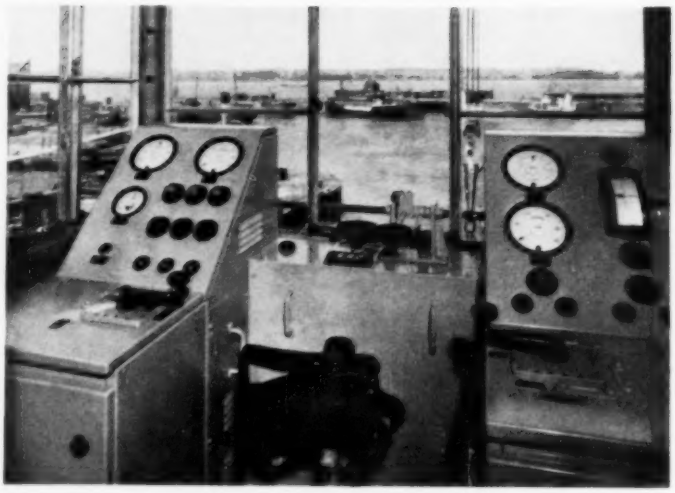

Fig. 6.—Crane operator's control desk.

SLEWING AND BALLAST MOTORS.

Series-wound slewing and ballast motors are employed, and these are supplied direct from the auxiliary generator system. The 45 h.p. slewing motor is energized through a 6-notch controller and a contactor starter. This starter is fitted with a timing device to prevent the motor being accelerated too rapidly by the operator, who nevertheless retains full control over the final speed of slewing. A diverter resistor on the first two notches permits creep-speed slewing.

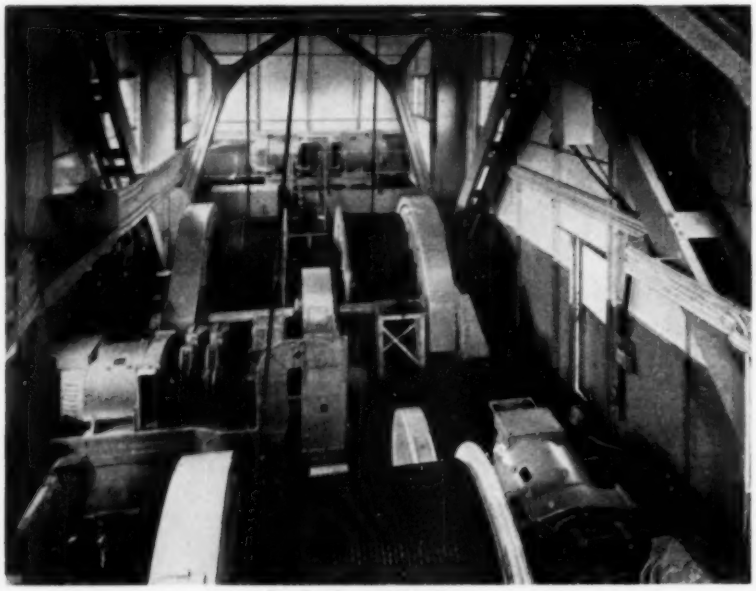

Fig. 7—Crane Motor Room

Speed and direction of the 20 h.p. travelling-ballast motor are varied by a 7-notch controller, and a position indicator working on the potentiometer principle shows the location of the ballast trucks. Warning lights indicate if the forward or backward limit switches trip. Creep-speed operation is obtained by shunting the motor armature with diverter resistors.

CONTROL CABIN.

All controls for the operator are housed in a cabin at the front of the crane superstructure. Two consoles, one on either side of the operator's seat, contain warning lights, pushbuttons, ammeters and other indicating instruments. One of the consoles also carries the slewing-motor controller and the other the travelling-ballast controller. Immediately in front of the operator is a cabinet, the top of which carries the 3-position rotary switch for selecting either of the hoists or the derrick motor. A lamp in one of the consoles indicates the motor chosen. Adjacent to this switch is the lever-type 9-notch controller for speed variation of the selected motor. Interlocks are fitted to ensure that the selector switch can only be operated when the controller is in the 'off' position. Pushbuttons are also provided to enable the operator to override the top limit switches of either of the hoists or the derrick motor, and red warning lamps show when this has been done.

A Crystallographic Survey of Carbons

By E. G. STEWARD, B.Sc., Ph.D., F.Inst.P., and
B. P. COOK, B.A. (Hirst Research Centre).

INTRODUCTION: THE RANGE OF CARBONS.

FEW elements are of more instrinsic interest and industrial importance than carbon. It occurs naturally in coal, anthracite, graphite and diamond, and in addition large quantities of widely differing 'artificial' carbons (e.g., carbon blacks, artificial graphites, activated charcoals) are manufactured annually. A high-rank coal can be a purer source of carbon than a naturally occurring diamond; the former may contain as much as 95% carbon and the latter as much as 20% impurity.

Coals and anthracites are all poorly crystalline but, nevertheless, they differ quite markedly in their physical properties and in the extent to which their structures change on heat-treatment. Natural graphite and diamond are both highly crystalline, but whereas graphite has a very anisotropic aromatic layer-structure, the diamond structure is isotropic, each carbon atom being tetrahedrally co-ordinated to its nearest neighbours. Very strong carbon bonds within the layer planes and very weak interlayer bonding make graphite a soft, lubricating material. In contrast, the three-dimensional symmetry of the bonding in diamond makes the structure one of extreme hardness although the strength of the bonding is rather less than that of the in-plane bonding in graphite.

Carbons prepared commercially and experimentally are in general obtained by suitably controlled thermal decomposition of organic materials; the properties of the carbons differ enormously depending on the particular conditions of preparation and subsequent heat-treatment. Factors which can affect the nature of the product include the chemical composition and/or physical state of the substance being carbonized, the rate of heating and temperature of carbonization, the pressure applied during carbonization, the presence of solid surfaces and the impurity content. When a hydrocarbon gas, for example, is allowed to impinge at atmospheric or reduced pressures on to a graphite substrate heated to a temperature of between 900° C and 2000° C, a hard shiny carbon deposit is obtained whose exact nature is dependent on the temperature of deposition but is virtually independent of the chemical composition of the parent hydrocarbon[1, 2]. If, however, pyrolysis of the same hydrocarbon gas occurs, not in contact with the solid surface but in the vapour phase, then soft, sooty carbons are obtained whose properties are now influenced by the chemical composition of the parent hydrocarbon.

The sooty carbon blacks are used in the rubber industry and in the manufacture of primary batteries. The hard, shiny carbon deposits have properties which make them potentially attractive for various specialist applications such as resistors and missile nose-cones. They can be shown to consist of relatively small, imperfect graphite crystallites oriented with their basal layer planes parallel to the substrate surface; the preferred orientation of the crystallites confers on the material highly anisotropic electrical and thermal properties, facilitates crystal development on heat-treatment, makes it nearly impermeable to gases and also oxidation resistant (because oxygen tends to attack preferentially the edge atoms of the graphite layer planes).

For nuclear engineering purposes and for use as electrodes in the electrochemical industries, solid carbon blocks of extreme chemical purity and high mechanical strength are required. These normally are made[3] from finely-crushed petroleum coke (the residue from the distillation of crude petroleum oils) mixed with sufficient coal-tar pitch to coat the coke particles evenly. The coke and pitch mixture is extruded or moulded to the required shape and then carefully heated to approximately 1000° C to carbonize the binder and produce a rigid body. Heat-treatment in a graphitizing furnace to a temperature of between 2500° C and 3000° C follows to remove residual hydrogen and other impurities. This high-temperature heat-treatment permits extensive crystal growth and the final product is a highly graphitic material which, though easily machined, has considerable mechanical strength.

THE CRYSTALLOGRAPHY OF CARBONS (EXCLUDING DIAMOND).

The crystal structure of perfect graphite was deduced by J. D. Bernal[4] in 1924. The crystal structures of all actual graphites deviate to a greater or lesser extent from the ideal structure but even in many so-called 'amorphous' carbons small graphite-like layer planes exist.

The carbon atoms within a graphite layer plane

form a regular hexagonal network with a C-C distance of 1·42 Å. In perfect graphite, as described by Bernal (fig. 1*a*), the layer planes are stacked parallel to each other and 3·354 Å apart; they are in three-dimensional register such that (1) half the carbon atoms in one plane are directly above atoms in the layer beneath while the other half are directly above the centres of the hexagons in the layer beneath, and (2) all the carbon atoms in alternate layers are directly above one another. This alternating (*ABAB*——) stacking sequence results in a hexagonal unit cell.

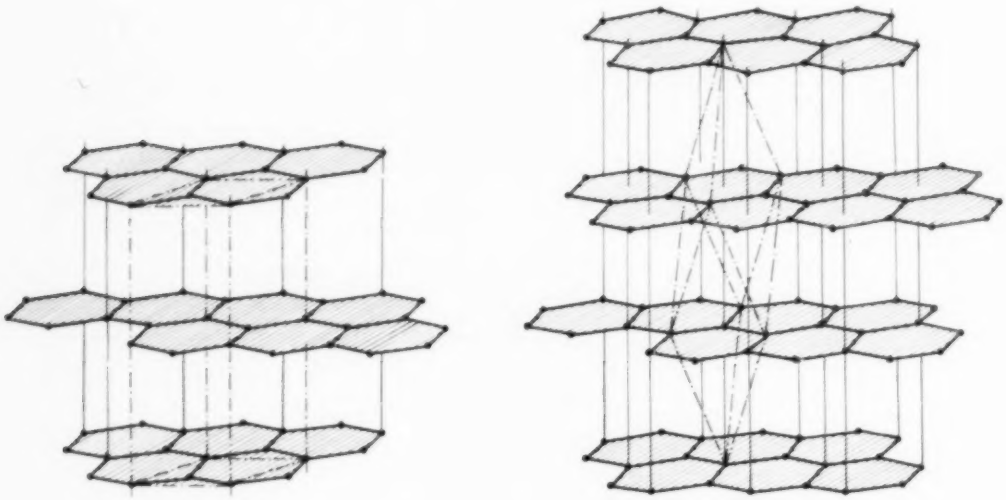

Fig. 1.—Diagrammatic representation of the fully ordered graphite crystal structure: (a) hexagonal form; (b) rhombohedral form.

It is evident from fig. 1*b* that a different regular three-dimensional lattice can be obtained by stacking the layer planes such that condition (1) above is still fulfilled, but such that the carbon atoms in every third layer plane, instead of alternate layer planes, are superposed. This alternative lattice, with stacking sequence *ABCABC*——, has a rhombohedral unit cell; it was first postulated by Debye and Scherrer[5] and was shown by Lipson and Stokes[6] to account for certain weak lines in the X-ray diffraction patterns of natural and well-crystallized artificial graphites which could not be attributed to the hexagonal (Bernal) structure (fig. 2).

The energy difference between the two structures is very small, the hexagonal modification being slightly the more stable at all temperatures; the rhombohedral form is readily transformed to the hexagonal by heating at temperatures above 1200° C[7,8]. The proportion of rhombohedral structure in natural graphites and good artificial graphites, as formed, is only a few per cent[8, 9, 10], but the proportion can be considerably increased (to approximately 25%[9]) by powdering and grinding. Detailed studies[8] of the effect of various stress systems on single crystals of hexagonal structure have shown that a combination of both unidirectional pressure and shear stress is necessary to produce the rhombohedral form. Although, due to weak interlayer binding energy, it might be expected that layer movement would occur readily, it is perhaps surprising that grinding produces not just random faulting of the stacking sequence but domains of rhombohedral structure sufficiently large to give sharp X-ray diffraction lines.

In the preceding discussion only those layer planes stacked in three-dimensional register with their neighbours have been considered. In all actual graphites, as opposed to the ideal structures, there is a lateral or rotational displacement of some of the layer planes from the specific stacking positions. The layer planes so displaced are randomly situated throughout the structure and, unlike the rhombohedral form, do not constitute a separate phase. Grinding, in addition to increasing the proportion of rhombohedral stacking in graphites, is found to increase the proportion of disoriented layer planes[11].

In natural graphites and graphitized cokes the proportion of disoriented layer planes is small, but in poorly crystalline 'non-graphitic' materials (e.g., carbon-blacks and cokes treated at temperatures below 1500° C) the layer planes, although remaining parallel, are in essentially random orientation about an axis

normal to the layers, i.e., the stacking is turbostratic[12]. In some very poorly graphitic materials, small isolated graphite layer planes exist in a matrix of non-organized material[13, 14].

The general resemblance between the X-ray diffraction powder patterns of a typical ' non-graphitic ' carbon and of a natural graphite is demonstrated in fig. 2. The diffuseness of the reflections given by the ' non-graphitic ' material is due primarily to the small size of the diffracting units (i.e., the crystals); the unsymmetrical nature of the *10* and *11* reflections is due to the turbostratic stacking of the layer planes. By a Fourier integral analysis of such a diffraction pattern, Warren[15] (1934) was able to demonstrate directly the presence of graphite-like layers in materials which had been previously called ' amorphous '. He later[16] (1941) derived formulae which enable the average diameter of the graphite layer planes and the proportion of non-organized material to be deduced from the breadth and intensity respectively of the unsymmetrical *hk* bands.

Also shown in fig. 2 is the diffraction pattern of a partially graphitized carbon having approximately two-thirds of the layer planes in three-dimensional register with their neighbours. It can be seen that for this sample the unsymmetrical *hk* bands are beginning to modulate into normal symmetrical *hkil* reflections; the degree of modulation is one method of determining p, the proportion of disoriented layers. Another and simpler method of determining p is from the average interlayer spacing; this can be deduced from the peak positions of the *000l* reflections. In a partially graphitized carbon the space between correctly oriented layers is 3·354 Å and between disoriented layers it is 3·44 Å; the observed interlayer spacing will have some intermediate value depending on the particular value of p[17, 18]. In a completely turbostratic carbon the interlayer spacing can be greater than 3·44 Å, but it reaches this value before any ordering can occur.

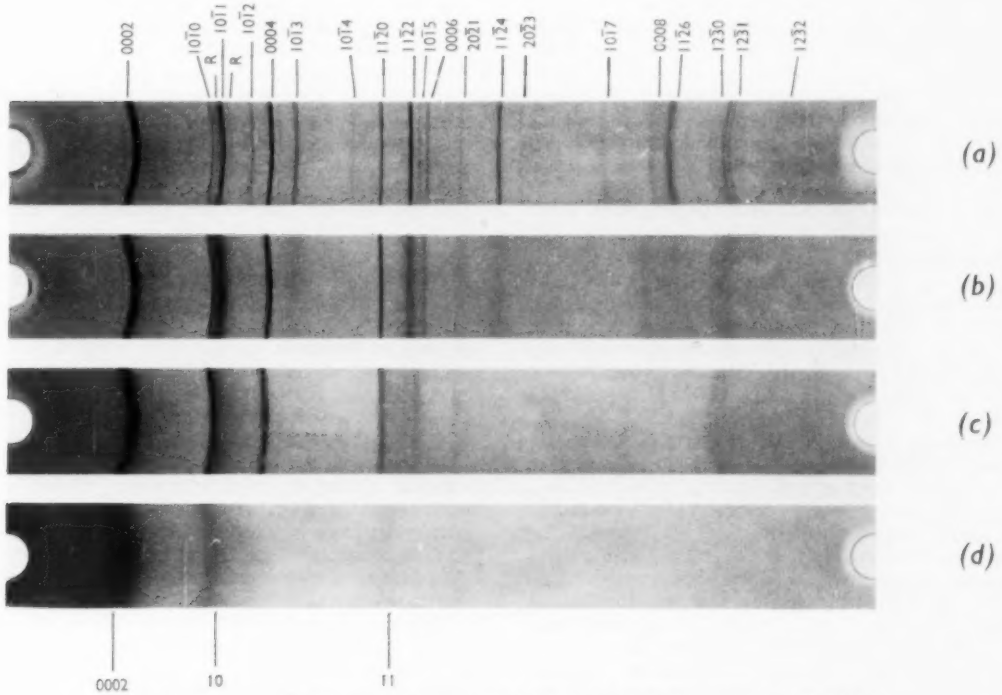

Fig. 2.—X-ray powder-diffraction photographs of (a) Natural (Ceylon) graphite, $L_a > 1000$ Å, $L_c > 1000$ Å, $p \simeq 0{\cdot}05$; (b) Petroleum coke heat-treated at 2200° C, $L_a \simeq 400$ Å, $L_c \simeq 200$ Å, $p \simeq 0{\cdot}35$; (c) Pitch-petroleum artefact heat-treated at 2100° C, $L_a \simeq 130$ Å, $L_c \simeq 130$ Å, $p \simeq 0{\cdot}95$; (d) Untreated carbon black, $L_a \simeq 16$ Å, $L_c \simeq 20$ Å, $p \simeq 1{\cdot}0$. (11·46 cm camera, CuKα radiation. hkil values for the diffraction maxima are shown; R denotes presence of rhombohedral stacking).

A useful appraisal of the degree of graphitization of a given carbon (i.e., the extent to which the perfect graphite structure is developed) can be made in terms of (*i*) p, the proportion of disoriented layers; (*ii*) d, the average interlayer spacing, and (*iii*) L_a and L_c, the average dimensions of the 'parallel-layer groups', parallel and perpendicular to the layer planes. In well-crystallized specimens of natural graphite L_a

and L_c are a few thousand Å and p is less than 0·05; in non-graphitic materials $p=1$ and L_a and L_c can be as small as 10Å. The minimum size of L_a for which the interlayer forces are sufficient to produce some three-dimensional ordering of layer-planes is approximately 100 Å[19].

For a complete description of a given carbon it is necessary to consider, as well as those parameters describing the size and perfection of the crystalline units, various ' extra-structural ' factors. These include the amount and nature of the non-organized material (completely amorphous carbon, organic residues involving O, H, N, etc.), the degree of porosity and the extent of mutual preferred orientation of the crystallites. Some information concerning the ' extra-structural ' factors can be obtained by suitable X-ray examination.

Recently, the suggestion has been revived that in some non-graphitic carbons, structures other than the graphite-like parallel-layer structure occur. Ergun and Tiensuu[20] have shown that *small* tetrahedrally-bonded alicyclic layers can give rise to diffraction effects similar to those given by *small* aromatic graphite-like layers and they conclude that from X-ray evidence alone it is difficult to ascertain if graphite-like or diamond-like, or both, structures are present in ' amorphous ' carbons. Electron diffraction is slightly more effective than X-ray diffraction in studying short-range order because the high energy electrons are equivalent to a shorter wavelength radiation. An electron diffraction study by Gjonnes[21] of ' amorphous ' carbon films obtained by evaporation indicated that the observed atomic radial distribution of carbon atoms (i.e., the average distribution of carbon atoms about any given atom) did not agree as well with that calculated for a planar graphite structure as with that calculated for the non-planar carbon structure originally proposed for certain carbon chars by Gibson and others[22], mainly from chemical and stereochemical considerations. This structure is a three-dimensional network of the 6-ring carbon groups found in graphite and staggered 8-ring carbon groups having the longer carbon-carbon bonding associated with the diamond structure. Similar work on carbon films by Kakinoki and others[23] has also indicated that two types of bonding are present; these authors, however, suggest that small, randomly oriented regions of graphite-like and diamond-like structure coexist. On heat-treatment of their carbon films[24] to temperatures between 500° C and 1200° C a gradual transformation of the structure to one containing only graphite-like layer planes was observed.

Even though the diamond-type configuration is evidently thermally unstable it cannot be disregarded in considering graphitization processes (i.e., the development of the graphite structure on heat-treatment). It is well known that the degree of graphitization that can ultimately be achieved is essentially determined by factors such as porosity, cross-linking and crystallite orientation, that are established during the low-temperature (<400° C) carbonization process. It is possible that, as has been suggested[20], the diamond-like bonding is only present in appreciable quantities in those ' non-graphitic ' carbons that do not become graphitic on subsequent heat-treatment. Further electron diffraction studies of ' non-graphitic ' carbons that are known to become highly graphitic on heat-treatment are evidently desirable, to give support to, or to disprove, this suggestion.

THEORIES CONCERNING THE GRAPHITIZATION PROCESS.

The graphitizability of carbons on heat-treatment is dependent on the initial size of the ' parallel-layer groups ', on the mutual orientation of these groups and the way in which they are linked together. Linkages may occur directly through peripheral carbon atoms or they may also involve completely disorganized material (carbon or residual impurites) or, as suggested above, tetrahedrally co-ordinated carbon regions.

In 1951, Rosalind Franklin attempted[25] to unify the theories on carbon materials, particularly with respect to their behaviour on heat-treatment, by proposing that all carbons (except certain intermediate-rank coals and anthracites) could be sharply divided into either (*a*) ' graphitizing ', or (*b*) ' non-graphitizing ' carbons. It was moreover suggested that these two categories could be clearly distinguished in the early stages of crystallite growth, a well-defined relationship between L_a and L_c existing for each type of carbon. The L_a, L_c curves for ' graphitizing ', and ' non-graphitizing ' carbons are shown in fig. 3*a*.

It has since been established[26] that many carbons exhibit intermediate graphitizing behaviour; the classification into the two categories was an over-simplification arising from the choice of materials studied. It nevertheless serves a useful purpose in defining the extremes of crystal growth behaviour.

' *Non-graphitizing* ' carbons are hard, porous materials formed from substances with small hydrogen content or appreciable oxygen content (e.g., the char obtained from polyvinylidene chloride, $(C_2H_2Cl_2)_n$ and sugar charcoal). On heat-treating these materials there is some initial growth, mainly in the L_a direction by incorporation of the non-organized carbon at the edges of the layer planes, but, even at temperatures of 3000° C, the crystallites virtually cease development beyond $L_a \simeq 70$ Å and $L_c \simeq 40$ Å, and the layer planes remain disoriented. To explain the limited growth and to be consistent with the observed hardness and microporosity of these materials, Franklin suggested that during low-temperature carbonization a rigid system of cross-linking between the crystallites is developed; this cross-linking is preserved for the most part at higher temperatures and prohibits the coalescence of crystallites necessary for graphitization to occur. Reference has already been made to the possible initial presence of tetrahedral bonding in this type of material.

' *Graphitizing* ' carbons are soft, compact materials formed from substances rich in hydrogen (e.g., pitch and petroleum cokes, and the char obtained from polyvinyl choride $(CH_2Cl)_n$). The presence of a large amount of hydrogen in the starting material results in the formation of hydrocarbon decomposition products

during the initial carbonization and any cross-links formed between neighbouring crystallites are subject to continual reduction. The absence of strong cross-linking and the shape of the individual crystallites (parallel-layer groups) produce a compact carbon showing a strong tendency for neighbouring crystallites to be oriented with their layer planes nearly parallel to one another. As with the non-graphitizing carbons the initial crystallite growth is mainly in the layer diameter, L_a, by incorporation of non-organized carbon, but on further heat-treatment considerable crystallite growth occurs due to basal plane stacking and edge-union of the layer planes facilitated by their mutual orientation.

Once the non-organized material has been used, it appears that there is initially a preferential growth in the average crystal height, L_c. At higher temperatures, however, the average crystal diameter, L_a, increases more rapidly than, and ultimately becomes greater than, L_c (fig. 3*b*). The temperature at which the ' cross-over ' between the L_a and L_c values occurs, and also the ultimate L_a and L_c values attained, vary from one material to another. To explain the ' cross-over ' it has been suggested[27] that lateral growth takes place by (*a*) edge union between layer planes, followed by (*b*) ordering within the enlarged layers. Due to the preferred orientation, the mobility of layer planes in graphitizing carbons is high, and (*b*) is the rate-controlling process: at the lower temperatures particularly, the layer planes are mosaic and the true values for the average whole-layer diameter are much larger than the observed L_a values, which are values for the average diameter of the ordered sub-regions only.

The crystal development of a petroleum coke with increasing temperature is shown in fig. 4[28]. It can be seen that whereas there is a more or less uniform increase in the crystal height, L_c, with increasing temperature, there is a very sudden increase in the apparent layer diameter, L_a, at approximately 2000° C; this is probably associated with the onset of ordering within the mosaic layer planes. As would be expected there is at this temperature a correspondingly large decrease in p, the proportion of layers not in correct register with their neighbours.

That crystallite growth in carbons occurs by the movement of whole layer-planes, or groups of layer-planes, and is not dependent on the migration of single atoms from one crystallite to another, is evidenced by the fact that growth occurs with measurable speed over a whole range of temperatures (from 1000° C to 3000° C). If the growth mechanism depended on atom-by-atom displacements, it would involve the breaking of carbon-carbon bonds: this would need a high energy of activation and would be a high-temperature reaction occurring with a measurable velocity only in a limited temperature range. Also if growth occurred solely by single atom migration, the observed differences between the behaviour on heat-treatment of the various carbons would not arise, as porosity and cross-linking could not effectively inhibit the growth process.

It is implicit in these theories that the energy required for the displacement of the layer planes is derived from the energy of thermal motion of the

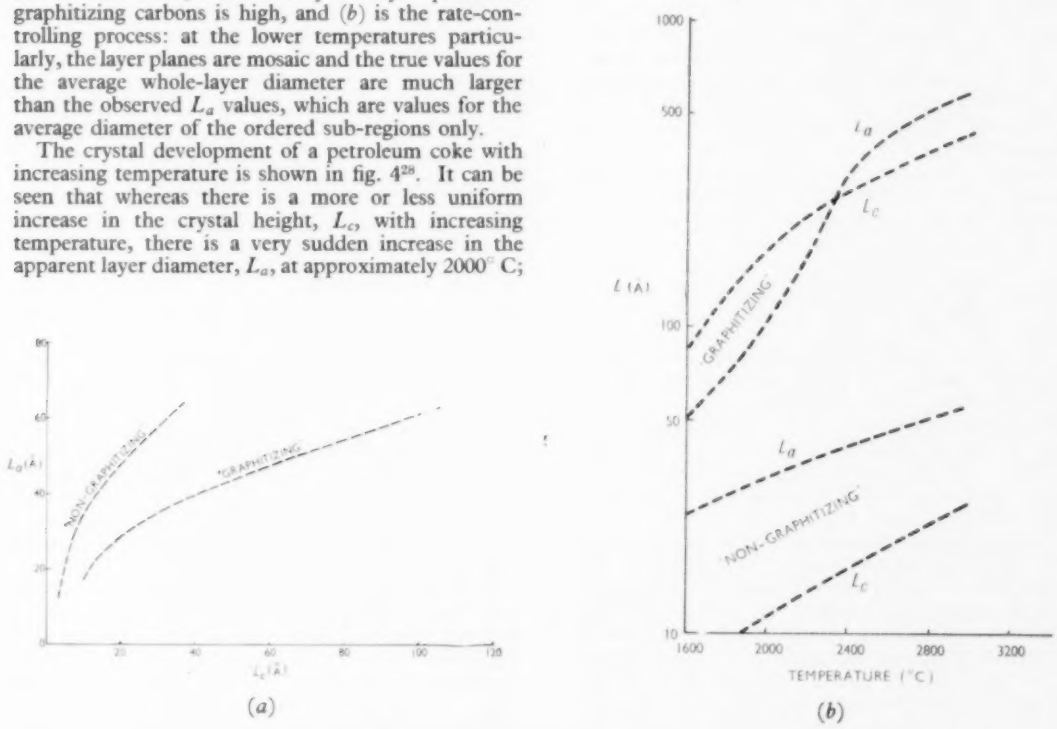

Fig. 3.—' Graphitizing ' and ' non-graphitizing ' behaviour: (a) L_a, L_c criteria for ' graphitizing ' and ' non-graphitizing ' carbons; (b) Typical example of high-temperature behaviour.

atoms. Mrozowski[29], however, does not consider that this alone is sufficient to cause appreciable growth; he suggests that anisotropic expansion of the crystallites on heat-treatment creates local stresses which can only be relieved by rearrangement and coalescence of the crystallites. To support this theory he observes that crystallite growth is less in a material which is powdered after heat-treatment at 1000° C and subsequently heat-treated to graphitizing temperatures than in similarly heat-treated, unpowdered material. It is suggested that powdering prevents the development of thermal stresses as great as those within the unpowdered material.

If for any reason rearrangement of the crystallites were not possible, the thermal stresses should eventually disrupt the material and some evidence for this has been observed with carbon blacks (i.e., soots). In carbon blacks crystallite growth is eventually limited by particle size: when carbon blacks are heat-treated the crystallite dimensions attain certain limiting values which are approximately one-third of the particle diameter[30, 31]. If heat-treatment is continued to temperatures considerably above those required to attain the limiting crystal dimensions, breakage of the particles might be expected. Breakage of carbon black particles has, in fact, been observed in electron microscope studies by Kuroda and Akamatu[32].

Whether crystallite growth depends on structural rearrangement due to thermal stresses, or to layer movement due to thermal motion, it would be expected that duration of heat-treatment would be of secondary importance to temperature of heat-treatment. Experiments in these laboratories have shown that the maximum crystallite development of a petroleum coke that can be attained at any particular temperature is virtually attained in under 60 minutes; with carbon blacks the growth ' saturation ' at any particular temperature is almost achieved within 15 minutes[26].

Recent considerations[33] of the graphitization processes in highly oriented carbons (e.g., pyrolytically deposited carbons, anthracites and lamellar coke grains) have suggested that in general too great an ultimate and exclusive importance is attached to the dimensions, L_a and L_c, measured by X-ray diffraction. It is suggested that a better understanding of the growth processes would be obtained if the dimensions of larger mosaic, ' M ', units were given greater consideration. Within the mosaic units there will be appreciable three-dimensional near-parallel alignment of the parallel-layer groups: graphitizability of the carbon will be dependent on the average L to M ratios and on the particular misorientation between the ' L-unit ' sub-blocks. A diagrammatic representation of the suggested new parameters, M_a and M_c, is shown in fig. 5. Coalescence of ' M ' units on heat-treatment as well as ordering within the ' M ' units is feasible.

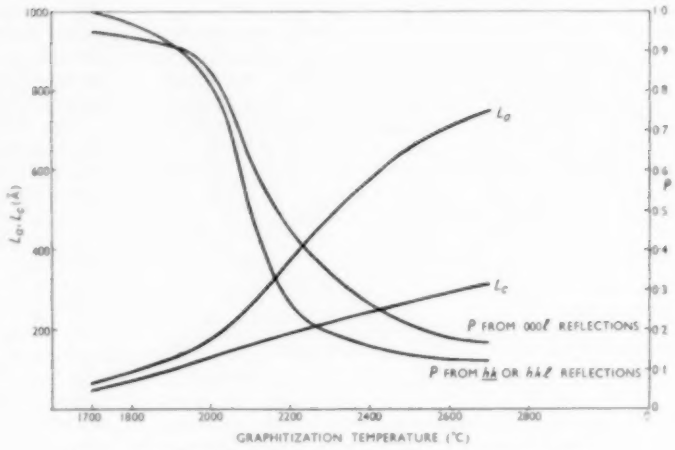

Fig. 4.—Crystallite development on heat-treatment of petroleum coke.

The variation of graphitizability of pyrolytically deposited carbons with temperature of deposition is readily understood in terms of mosaic domains. It is observed[33] that carbons deposited at temperatures of between 900° C and 1600° C become more highly graphitic when subsequently heat-treated to say 2500° C, than carbons deposited at 1700° C to 2000° C and similarly heat-treated. It is suggested that during the high-temperature deposition there is sufficient mobility of individual carbon atoms for the L units to order into the M units; little development, therefore, occurs on subsequent heat-treatment. In contrast, deposition at low temperature leads to quenched nucleation and small L units; however large mosaic M units, characteristic of deposited carbons, facilitate the observed graphitization on subsequent heat-treatment.

It is frequently observed[33, 34, 35] that in particularly highly oriented materials, unlike the more normal ' graphitizing ' carbons discussed previously, the L_c dimension is as large as or greater than L_a after heat-treatment at high temperatures. It would seem, therefore, that in these very highly oriented samples either basal plane realignment occurs more readily than ordering within the enlarged layers (i.e., L_c tends to M_c more readily than L_a tends to M_a) or alternatively M_c is initially larger than M_a.

X-ray microbeam examination[36] and electron diffraction studies[37] have indicated the existence of the textured ' mosaic ' units in natural graphites and petroleum cokes. It is interesting too that electron microscope studies of Moiré fringes[38, 39], indicate grain sizes in cokes considerably larger than the L dimensions obtained by X-ray diffraction; it would seem that in practice X-ray diffraction is more sensitive to small misorientations between mosaic sub-blocks than Moiré fringe techniques.

GRAPHITE FOR NUCLEAR REACTORS.

The advantages of graphite as a structural component of nuclear reactors include its low cost, chemical purity, high neutron moderating efficiency, low neutron absorption cross-section, high mechanical strength and good refractory properties. The disadvantages include the anisotropic dimensional changes and the considerable decrease in thermal conductivity which occur on neutron irradiation. Also, because imperfections in the crystal lattice can be produced by irradiation and the internal energy of the structure consequently increased, regular annealing of the graphite has to be considered for preventing accumulation of sufficient stored energy to cause a spontaneous increase in temperature.

The manufacture of coke artefacts for use as neutron moderators has been briefly considered in the introduction. These artefacts are essentially two-component systems of petroleum coke and pitch-binder coke. Experiments at the Hirst Research Centre have shown that the strength and other mechanical properties of artefact samples do not depend as much on the binder-coke bridges as on the crystal structure of the grist material. Crystal growth measurements (L_a, L_c and p) indicate that after similar heat-treatments the average crystal development of a pitch-petroleum artefact is slightly less than that of a petroleum coke alone; two distinct graphites in the artefact samples are not observed. It is probable that the graphitizability of the petroleum coke is affected by the presence of the pitch binder (due to penetration of the binder into the petroleum coke pores or to additional surface constraints on the petroleum coke grains) but it is also possible that the observed reduced crystallite development results partly from averaging the crystal parameters of a petroleum coke with those for a rather less graphitic pitch coke. The graphitizability of *control* samples of both pitch coke and petroleum coke is being examined; published data on other coke samples would seem to indicate that in general pitch cokes are less graphitizable than petroleum cokes.

In addition to the graphite blocks required for structural and neutron moderation purposes, there is a nuclear engineering demand for impermeable graphites suitable for use as fuel-element containers and as sleeves for coolant systems. A millionfold reduction in the permeability of normal moderator graphite can be obtained by deposition of carbon within the pore structure. This is achieved[41, 42] by (*a*) forcing a hydrocarbon gas through the heated graphite so that cracking of the gas occurs within the pores, or (*b*) impregnating the graphite with liquid hydrocarbons (sugar solution or furfuryl alcohol are found to be particularly suitable) and subsequently carbonizing the impregnant. Alternatively, by suitable pyrolytic decomposition of gaseous hydrocarbons onto the heated moderator graphite, a surface film can be obtained which reduces the permeability of the graphite: the surface deposit, however, has the undesirable tendency to flake off from the substrate.

Impermeable carbons have also been prepared at the Hirst Research Centre by the careful carbonization and heat-treatment of certain high-polymer materials. These carbons do not show any preferred crystallite orientation and are ' non-graphitzing '. As with other ' non-graphitizing ' carbons they are highly porous after heat-treatment at temperatures less than 100° C, but unlike other ' non-graphitizing ' carbons, the limited crystal growth that occurs on further heat-treatment closes the micropores and produces a gas-tight structure.

A carbon subjected to irradiation in a nuclear reactor

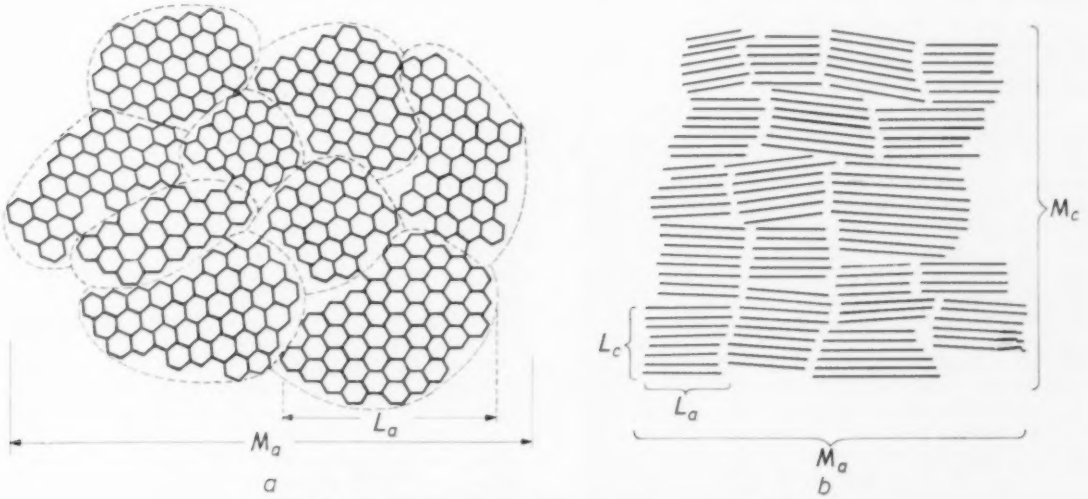

Fig. 5.—Diagrammatic representation of mosaic parameters M_a, M_c in relation to L_a, L_c: (a) Plan view of oriented macro-unit; (b) Elevation of oriented macro-unit. (Z. Krist., 114, 245, 1960).

suffers considerable structural degradation and consequent changes in physical and mechanical properties. The changes observed for bulk material are dependent not only on crystal structure changes, but also on the degree of preferred orientation of the crystallites, and on the volume and spatial distribution of pores.

Early X-ray investigation of crystal structure changes established that irradiation causes an expansion of the *c*-dimension of the crystallographic unit cell and a much smaller contraction of the *a*-dimension. (These cell dimensions are perpendicular and parallel respectively to the layer planes (fig. 1*a*). It is believed that under neutron bombardment some of the carbon atoms are ejected from their usual sites and that these primary ejected atoms in turn displace further atoms. A proportion of the displaced atoms, primary and secondary, eventually return to normal lattice sites but most of them are trapped between the layer planes. The trapped atoms force the layer planes apart locally, causing the observed increase in the average *c*-dimension; the small contraction in the *a*-dimension could be due to a slight distortion of the hexagonal networks owing to the vacant lattice sites and/or to a slight puckering of the layers around the interstitial atoms. Bacon and Warren[43] have shown that the changes in cell dimensions are linear functions of radiation dose, at least up to radiation doses sufficient to produce an 8% expansion in the *c*-dimension.

From a series of experiments with carbons whose initial degree of graphitization varied from poorly graphitic (p=0·83) to highly graphitic (p=0·14), Bacon and Warren found[43] that the same irradiation treatment produces approximately the same percentage degradation of the structure, as measured by the percentage expansion of the *c*-dimension, irrespective of the initial degree of perfection. Comparisons, also, of the angular shift after irradiation of the *0008* and *11$\bar{2}$6* reflections (reflections not dependent and dependent respectively on ordered stacking) suggested that the interstitial atoms are able to push apart the neighbouring layer planes equally effectively whether these are correctly oriented or not.

A comparison of the X-ray diffraction patterns of increasingly irradiated graphites and an unirradiated control, shows that not only are the reflections shifted by progressively increasing amounts due to changes in lattice dimensions, but also each reflection becomes increasingly diffuse. A graphite, initially highly crystalline, but irradiated sufficiently for an 8% expansion in the *c*-dimension to occur, would give a diffraction pattern similar to that of a very poorly graphitic carbon; i.e., due to irradiation the pattern would change from one resembling fig. 2*a* to one resembling fig. 2*d*. Fourier analysis of the reflection profiles indicates[44], however, that at radiation doses less than 1000 MWd/ton (corresponding to an approximately 6% change in *c*), the broadening of the reflections is due to strain distortion of the crystal structure produced by the interstitials, rather than to crystallite break-up, or to reduction in stacking perfection. It is probable that in extremely heavily irradiated samples, some crystallite break-up does occur.

At moderate doses the fact that comparatively low annealing temperatures (less than 1500° C) are required to produce complete structural recovery shows that little or no break-up of crystallites occurs. If break-up of the crystallites did occur, the annealing treatment would become equivalent to a regraphitization treatment and very high temperatures (greater than 2500° C) would be required.

At any particular low annealing temperature most of the recovery which will occur at that temperature has taken place within the first few minutes[43]. It is found that, even for moderate radiation doses, the more heavily irradiated samples require a higher annealing temperature to achieve structural recovery than the less heavily irradiated samples, i.e., the type of defect

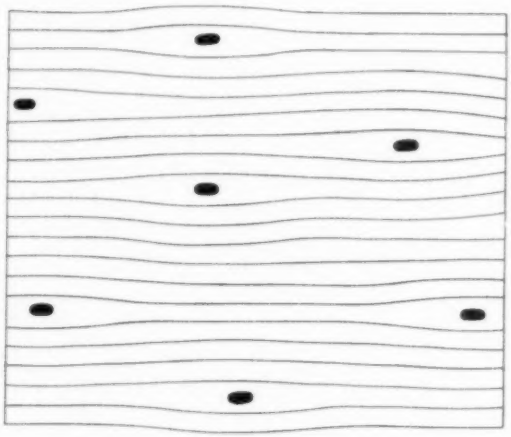

Fig. 6.—Schematic representation showing approximate regularity in positioning of interstitials (after G. E. Bacon and B. E. Warren[43]).

produced as irradiation is continued becomes increasingly difficult to remove. It is probable that in the more heavily-irradiated samples some of the interstitial atoms coalesce to form larger disc-shaped units. Slight evidence in support of such units is found in the small-angle X-ray scattering studies of Warren and Chipman[45]. Recently, Eeles[46], also from small-angle scattering studies, has derived values for the average diameter of the coalesced units in several irradiated samples, but in this work, not altogether satisfactory corrections for ' white ' X-ray radiation effects appear to have been made.

If the temperature at which the graphite is maintained during irradiation is raised, damage to the crystal structure is considerably reduced; presumably the higher mobility of the displaced atoms causes a larger proportion to return more or less immediately to normal lattice sites or to migrate to the edges of the layer planes. It is of interest that increasing the temperature during irradiation has a smaller effect on the percentage *a*-contraction than on the percentage

c-expansion[47], possibly because vacancies cannot migrate as readily as interstitials to the crystallite edges.

Several models have been considered[43] in an attempt to correlate the X-ray diffraction effects shown by irradiated graphites with the nature of the damage to the crystal structure, i.e., the number and distribution of the displaced atoms and of the vacant lattice sites. The most satisfactory model would seem to be one in which the interstitials are situated in approximate regularity throughout the crystal lattice to produce an approximately regular array of increased interlayer spacings (fig. 5). (An exact regularity or completely random positioning of the displaced atoms would not give rise to the observed diffraction effects). The lateral extent of the increased spacing about an interstitial atom is small and the minimizing of distortion energy would lead to the fairly regular distribution of interstitials. Energy considerations also suggest a minimum stable separation of two interstitials between the same pair of layer-planes, so that in heavily irradiated samples the interstitials would tend to coalesce.

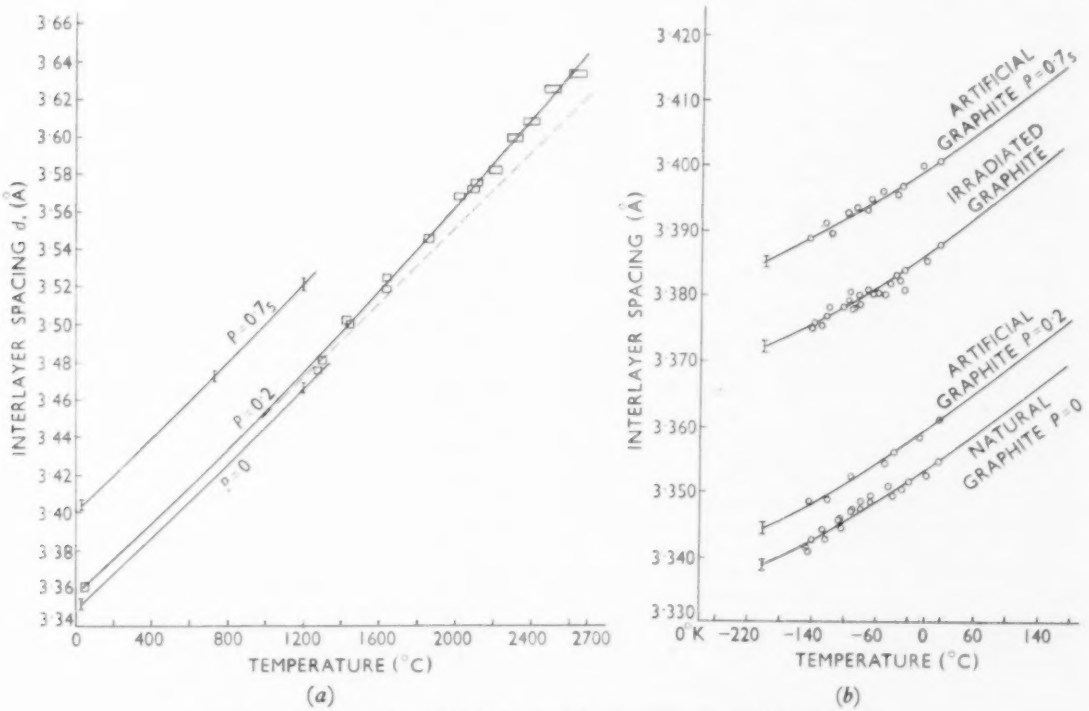

Fig. 7.—Interlayer spacings at (a) high and (b) low temperatures. (In (a) the dotted line is drawn to demonstrate the departure of the experimental curve from linearity).

THE THERMAL EXPANSION OF GRAPHITE.

An essentially linear relationship has been observed[48] between the macroscopic thermal expansion of reactor graphites and the macroscopic expansion produced by neutron irradiation. It is probable that in both instances much of the crystallite expansion is accommodated within the pore volume. An examination of the crystallite thermal expansion can provide information concerning the variation of interlayer binding energy with interlayer spacing[49], and whether or not the binding energy is the same for oriented and disoriented layers.

Owing to important inconsistencies and omissions in the literature concerning crystallite expansion, measurements have been made[50, 51] of the expansion of the interlayer spacing in carbons of widely differing graphitic perfection, over temperatures within the range -196° C to 2600° C. Special X-ray diffractometer techniques were developed for both the high ($>1000^\circ$ C) and low ($<20^\circ$ C) temperature measurements. The results are shown in fig. 7.

The high-temperature measurements on a graphite having 20% disordered stacking ($p=0{\cdot}2$) definitely established a non-linear relationship between interlayer spacing (d) and temperature (t); the expansion for a given rise in temperature increases slightly as the interlaying spacing increases and the binding energy decreases. The empirical equation derived to describe the experimental results in the temperature range 0-2600° C is $d_{p=0{\cdot}2}=3{\cdot}357+91{\cdot}9\times10^{-6}t+5{\cdot}3\times10^{-9}t^2$.

For graphites having $p=0$, and $p=0{\cdot}75$, measurements up to 1188° C indicate essentially similar curves translated parallel to the temperature axis; it would seem, therefore, that although rate of expansion is dependent to a slight extent (indicated by the small t^2 term in the equation) on the interlayer spacing, it is, for a given spacing, substantially independent of stacking disorder. It is of interest to recall that Bacon and Warren's[43] measurements indicated that the percentage expansion of the interlayer spacing produced by a given neutron irradiation treatment is independent of stacking disorder, too.

Measurements at low temperatures show, for each graphite examined, a 'levelling-off' in the rate of expansion with decreasing temperature. The results indicate that for carbons of different graphitic perfection there will be different limiting distances of closest approach between the layers as the temperature decreases to 0° K; i.e., misorientation between adjacent layers hinders their close approach. It is evident, moreover, from fig. 7*b* that low-temperature rate of expansion for a given interlayer spacing is dependent on stacking disorder effects too; in this temperature region the curves for varying perfection are again essentially similar but are translated parallel to the spacing axis.

The low-temperature measurements on a neutron-irradiated sample are of particular interest. Before irradiation this material had an interlayer spacing of 3·358 Å and 20% disordered stacking; the stacking perfection was not measurably changed by irradiation but the interlayer spacing increased to 3·388 Å. It is seen that the interstitials producing this increase in spacing have essentially the same inhibiting effect on the low-temperature contraction as the greater stacking disorder of an unirradiated less-graphitic carbon having the (room-temperature) interlayer spacing of 3·388 Å.

From measurements of the decrease with increasing temperature of the intensity of certain X-ray reflections, it is planned to determine the amplitude of thermal vibration of carbon atoms perpendicular to the layer planes, at temperatures up to 2600° C. Graphite is an unusual material in that its strength and elastic moduli increase with increasing temperature. Stress in graphite is relieved by the slipping of layer planes over one another; if the amplitude of the thermal vibrations increases more rapidly than the interlayer spacing with increasing temperature, then relative movement of the layer planes would be impeded. This could go some way to explaining the observed increases in strength and elastic moduli.

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TECHNICAL LITERATURE

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PERMEABILITY AND PERMITTIVITY MEASUREMENTS ON MICROWAVE FERRITES USING RESONANT CAVITY TECHNIQUES (789).*

By J. N. Rogers and J. Watkins (Research Laboratories).

Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, 2-7 *June*, 1958.

The insulating nature of some ferrite materials permits their application at microwave frequencies, where their gyromagnetic properties can be usefully employed in practical devices. In such devices it is not possible, from the overall performance, to distinguish between the effects produced by the electric and magnetic properties of the material, and measurement techniques by which these properties can be separately assessed are therefore required. The technique described uses resonant cavities and small ferrite specimens, of appropriate shape, and the changes in the resonant frequency and Q-value of the cavity, produced by insertion of a specimen, are measured.

MAGNETIC HYSTERESIS LOOPS OF SINGLE-DOMAIN THIN FILMS HAVING UNIAXIAL ANISOTROPY (802).*

By L. A. Thomas and M. Williams (Research Laboratories).

Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, 2-7 *June*, 1958.

The use in digital computers of magnetic storage elements having rectangular hysteresis loops is now well established. A potentially important newcomer among such elements is the magnetic thin film. In general, the latter shows a rectangular hysteresis loop for only one direction of measurement in the film. For other directions a variety of different shaped loops is observed, similar to those predicted theoretically by Stoner and Wohlfarth for a model of a single-domain having a unique axis along which the magnetization prefers to lie. This similarity suggests that a magnetic thin film may be regarded as a single domain with uniaxial anisotropy.

THE DESIGN AND PERFORMANCE OF A HIGH-SPEED SILICON DIODE (840).*

By M. J. Callé, B. Dale and C. A. P. Foxell (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 17, 1959.

With the increasing use of high-speed switching techniques a need has arisen for diodes with a fast transient response. The paper first considers the various methods by which the speed of semiconductor diodes may be improved by reducing carrier storage. In the silicon device described, this is accomplished by a reduction of the lifetime of the basic material. Of the two methods investigated, neutron bombardment and heat treatment, the latter was found to be the more effective. The heat treatment involves quenching the silicon from a temperature in excess of 1000° C.

The paper then discusses the effect on the static characteristics of diodes made from silicon quenched in this manner.

The methods of measuring the transient response of the device are discussed, and a comparison is made between them.

TRANSISTOR FEEDBACK AMPLIFIERS IN CARRIER TELEPHONY SYSTEMS (846).*

By D. F. Burman, L. J. Fey and D. G. W. Ingram (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 16, 1959.

Because equipment using transistors will be introduced into communication networks in which valve equipment is already in use, questions of compatibility will arise. In some cases the performance of transistor equipment will have to conform closely to that of existing valve equipment, while, in others, no such restriction will occur. With present transistors this latter case would lead to the use of low signal levels and low-gain amplifiers. With feedback amplifiers employed in carrier systems the effect is to divide the amplifiers into two classes. The first class must operate with high gains and high output powers, while the second class is essentially one of low-power amplifiers. Examples of both classes are described, and various features of their design are discussed.

THE POWER RATING OF SEMICONDUCTOR RECTIFIERS (853).*

By J. I. Missen (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 17, 1959.

The widespread use of semiconductor rectifiers, with their extremely high conversion efficiency, ability to operate at high reverse voltages and consequent small size, has brought in its train problems peculiar to these devices. It is most important, therefore, that the electrical ratings should be established on a systematic and rigorous basis.

In the paper, some of the factors which influence the rating of germanium and silicon junction rectifiers are considered, and the procedure for obtaining the curves of rectifier current rating as a function of ambient temperature is given. Determination of overload characteristics and the associated use of thermal-electrical analogue techniques are described.

THE GROWING OF 5 kg SINGLE CRYSTALS OF GERMANIUM (857).*

By J. G. Wilkes (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 17, 1959.

Consideration of the factors involved in the efficient production of semiconductor devices reveals the desirability of growing large single crystals of germanium. The technical specification for the material demands that this shall not be achieved at the expense of quality, i.e., the germanium must be of the correct resistivity, lifetime and disclocation density. The realization of the potential advantages has involved a range of problems, the solutions to which are described in this paper.

A RELIABILITY APPRAISAL OF SEMICONDUCTOR DEVICES (859).*

By R. Brewer and W. W. D. Wyatt (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 17, 1959.

The current problems of assessing the reliability of semiconductor devices are discussed, and reference is made to the order of reliability required in typical applications.

The evidence from life tests shows how variations in operating conditions and assessment levels affect the apparent reliability of the devices.

The incidence of inoperative failures, the trends shown by measurements of major characteristics during life, and the form of life-survival curves are discussed, and a brief reference is made to the equipment used in carrying out the tests.

THE MAXIMUM VOLTAGE, CURRENT AND POWER RATINGS OF JUNCTION TRANSISTORS (860).*

By R. A. Hilbourne and D. D. Jones (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 17, 1959.

The paper discusses the properties of a junction transistor which determine the limits of the three basic ratings, namely the maximum collector voltage, collector current and power dissipation, and describes methods of measurement. The effects of the limitations on the various circuit configurations are also discussed.

THE APPLICATION OF POWER TRANSISTORS TO THE OPERATION OF GAS-DISCHARGE LAMPS FROM D.C. SUPPLIES (865).*

By I. F. Davies and D. Dunthorne (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 107, *Part A, No.* 33, *June* 1960.

The operation of fluorescent tubes on high-frequency (up to 20 kc/s) supplies is considered. The characteristics of sine-wave and square-wave transistor inverters are discussed, and a preference is expressed for sine-wave supplies for lamp operation. Design details and component characteristics for sine-wave lamp inverters are considered and various types of circuit are mentioned.

THE DESIGN OF DIRECT VOLTAGE AND CURRENT STABILIZERS USING SEMICONDUCTOR DEVICES (871).*

By D. G. Wenham (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 106, *Part B, Supplement No.* 18, 1959.

The design of direct voltage and current stabilizers using semiconductor diodes and transistors is discussed, and a design procedure is given. The basic circuit considered is that in which a control element is placed in series with the supply and the load. The voltage across, or the current through, the load is compared with a reference and the difference is used to control the voltage drop across, or the current flowing through, the control element. The control is effected so as to keep constant the voltage across, or the current through, the load. Methods of achieving high stability against changes in input (or supply) voltage and changes in load are described. The effect of changes in ambient temperature on the output is considered and methods of minimizing this are given.

FUNDAMENTAL AND HARMONIC DISTORTION OF WAVES FREQUENCY-MODULATED WITH A SINGLE TONE (885).*

By R. G. Medhurst (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 107, *Part B, No.* 32, *March* 1960.

The distortion of single-tone frequency modulation by passive networks whose amplitude and phase characteristics are non-linear with frequency is considered in some detail. A new approximate formula has been developed by extension of earlier methods, and its use, supplemented by the quasi-stationary approximation and by direct Fourier analysis, permits evaluation of distortion levels over ranges of parameters previously excluded. A number of examples are given.

THE CORONA DISCHARGE AND ITS APPLICATION TO VOLTAGE STABILIZATION (891).*

By E. Cohen and R. O. Jenkins (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 107, *Part B, No.* 33, *May* 1960.

The properties of a gas discharge which make it suitable for voltage stabilization are discussed. Various types of corona discharge are described, and it is shown that a corona discharge between a wire anode mounted axially in a cylindrical cathode is the most suitable for voltage stabilization. To obtain the required low impedance it is necessary to use hydrogen as the filling gas. The effect of dimensions on the voltage and impedance of the discharge is discussed, and characteristics of various tubes which have been developed as corona voltage stabilizers covering a range of 350-7000 volts are shown. Finally some of the applications of such tubes and their appropriate operating conditions are given.

A PRELIMINARY STUDY OF SURFACE OXIDE PRODUCED BY REACTION OF CARBON AND CARBON DIOXIDE (893).*

By B. L. Tonge (Research Laboratories).

Proceedings of the Fourth Conference on Carbon, pp. 87-93, *Pergamon Press.*

The paper records some preliminary experiments on the formation and removal of surface oxide on carbon at temperatures below 600° C. The equilibrium constant and heat of reaction for the system $Cf + CO_2 \rightleftharpoons C(O) + CO$ are given for the case where reactor grade graphite is the experimental material. The nature and stability of surface oxides on a number of carbons are discussed; the influence of surface oxide on carbon gasification rates, nitrogen surface areas and the gas contents of carbons is outlined.

AN INTERPRETATION OF THE MECHANICAL BEHAVIOUR OF CARBONS (901).*

By H. W. Davidson and H. H. W. Losty (Research Laboratories).

Proceedings of the Fourth Conference on Carbon, pp. 585-591, *Pergamon Press.*

The authors have come to a consistent interpretation of the elastic properties of carbon and graphite. In brief, it is thought that graphite accommodates impressed stresses by way of resolved relative movement of the layer planes which make up the crystal structure of all carbons. This view explains the following phenomena: (1) The effect of neutron irradiation on elastic moduli; (2) The effect of impregnation and heat treatment on carbons; (3) The elastic moduli and their temperature coefficients for a variety of graphites; (4) The high-temperature creep properties of a variety of graphites; (5) The elastic hysteresis and dynamic damping (at low frequencies) of carbons and graphites before and after heat treatment and neutron irradiation. The application of these views to an understanding of the strength of carbons and graphites is considered.

THE PROBLEMS RAISED BY THE INFLUENCE OF NEUTRON IRRADIATION ON THE STRESS-STRAIN RELATIONSHIPS OF GRAPHITE (902).*

By H. H. W. Losty (Research Laboratories).

Proceedings of the Fourth Conference on Carbon, pp. 593-597, *Pergamon Press.*

It is known that the elastic moduli of graphite increase as a result of neutron irradiation. A novel problem arises when graphite is irradiated stressed (or strained) and the stress-strain behaviour is examined. This can be illustrated by considering a spring supporting a free weight. One can visualize two extremes of behaviour: on the one hand the change in modulus causes the weight to be lifted while on the other hand, the weight remains stationary but a permanent set is observed on removal of the weight. Furthermore, irradiation may induce some degree of ' plasticity ' which will result in a relaxation of strain (or stress). The available experimental evidence has been examined in this new light and the existence of an irradiation-induced plasticity is clearly demonstrated.

THE EFFECT OF IMPREGNATION AND HEAT TREATMENT ON THE PHYSICAL PROPERTIES OF GRAPHITES (907).*

By H. H. W. Losty (Research Laboratories).

Proceedings of the Fourth Conference on Carbon, pp. 671-674, *Pergamon Press.*

A new process of impregnating graphite with sugar solution has been developed for the purpose of reducing its permeability to gases. The effect of this non-graphitizing impregnant on the physical, mechanical and thermal creep properties of the graphite is considered. The data can be rationalized on the existing theory that the elastic and plastic deformations of graphite are accommodated within the structure by relative motions of the layer planes within the crystallites.

THE ALGEBRA AND TOPOLOGY OF ELECTRICAL NETWORKS (911).*

By P. R. Bryant (Research Laboratories).

I.E.E. Monograph No. 414E.

The paper gathers together the various results and methods used in an elementary algebraic and topological study of electrical networks. Considerations are restricted to networks containing a finite number of lumped resistors, capacitors and self and mutual inductors. The result is a connected logical presentation leading, by use of the concepts of incidence, loop and cut-set matrices, to the corresponding nodal, loop and cut-set analysis methods.

THE POISONING OF IMPREGNATED CATHODES (913).*

By R. O. Jenkins and W. G. Trodden (Research Laboratories).

Journal of Electronics and Control, Vol. 7, *No.* 5, *p.* 393, *November* 1959.

The poisoning of barium-calcium aluminate impregnated tungsten cathodes by various gases has been investigated experimentally. It is shown that oxygen, water vapour, carbon dioxide and air poison these cathodes, while carbon monoxide, nitrogen and hydrogen do not. Poisoning takes place with the former gases if a critical pressure, depending on the gas, is exceeded, this pressure increasing with cathode temperature.

A theory correlating the various observations is proposed, based on the probabilities of gas adsorption, and rates of barium production, evaporation and migration.

DETERMINATION OF GASES IN METALS BY VACUUM FUSION (914).*

By J. E. Still (Research Laboratories).

Iron and Steel Institute Special Report 68, 1960.

The gas contents of various less-common metals have been determined, including titanium, zirconium, molybdenum, and beryllium.

Apparatus is described for vacuum fusion, using both iron and platinum baths. It is designed for simplicity of operation and versatility in research investigations rather than for routine analysis. A number of useful safety features are incorporated.

TRANSFORMATIONS IN OXIDES OF ALUMINIUM AND IRON (917).*

By H. P. Rooksby (Research Laboratories).

Silicates Industriels, Vol. XXV, 1960, *No.* 7/8, *p.* 335-339.

During the dehydration of the hydrated oxides of aluminium and iron, ordered structure transitions occur. In such transitions parts of the atomic pattern of the hydrated phase are carried over to a large extent unaltered after dehydration. In this paper the term 'pseudomorphic' has been adopted to denote such ordered transformations. Besides giving an account of the 'pseudomorphic' character of the changes which are consequent upon decomposition of the monohydrates of alumina and iron oxide, some new aspects of the crystallography of the anhydrous oxides obtained are discussed.

IMPERFECTIONS IN YTTRIUM IRON GARNET CRYSTALS (922).*

By D. C. Doughty and E. A. D. White (Research Laboratories).

Acta Crystallographica, Vol. 13, *Part* 10, *October* 1960.

Yttrium iron garnet crystals grown by the fluxed-melt technique from lead oxide often contain inclusions of lead-rich phases. In large crystals these inclusions are oriented and regular. Photographs of crystal sections show them to be associated with an initial dendritic stage of growth. Limitations of the growth technique are discussed.

VARIATION WITH TEMPERATURE OF THE DISTRIBUTION COEFFICIENT OF INDIUM IN GERMANIUM (927).*

By M. A. Lee (Research Laboratories).

Solid-State Electronics, Vol. 1, *pp.* 194-201, 1960.

A relationship is derived for an alloyed-junction transistor giving the solid solubility of the emitter material (indium) in the base crystal (germanium) in terms of the slope of a plot of reciprocal current gain vs. emitter current. Measurements were carried out on batches of transistors alloyed at temperatures in the range 350-805° C. The form of the temperature variation of the distribution coefficient deduced from these measurements is in good agreement with that predicted by Hall down to about 550° C. Below this temperature the observed values of the distribution coefficient are higher than would be expected from Hall's relationship. A discussion of the possible causes of this divergence is presented.

THE REGROWN-DIFFUSED TRANSISTOR (928).*

By C. H. L. Goodman (Research Laboratories).

Solid-State Electronics, Vol. 1, *pp.* 188-193, 1960.

A new process for producing high-frequency *n-p-n* silicon transistors is described. The novel feature is the formation of a doubly doped region in contact with singly doped material by the direct melting of appropriately doped fragments on to the latter, followed by subsequent solidification. A diffusion cycle then enables the required transistor structure to be developed.

The new technique is not limited to silicon and has a number of attractive features, among them: simplicity of apparatus, relatively high rate of production and efficient utilization of material.

ETCH PITS AND DISLOCATIONS IN CADMIUM SULPHIDE CRYSTALS (930).*

By J. Woods (Research Laboratories).

British Journal of Applied Physics, Vol. 11, *pp.* 296-302, *July* 1960.

A technique is described for producing dislocation etch pits on *0001*, *000$\bar{1}$* and *10$\bar{1}$0* growth faces of cadmium sulphide crystals. Methods are also described whereby the dislocations are decorated by precipitation of either gallium or copper. The strongest proof that the etch pits are formed where dislocation lines cut the free surfaces is provided by (1) the characteristic etch pattern formed after indentation; (2) the densities of etch pits in intersecting low-angle grain boundaries; and (3) the coincidence of etch pits and decorated lines.

In conclusion, it is shown that the dislocation content can play an important part in determining some of the electrical properties of the crystals.

MEASUREMENT OF THERMAL DIFFUSIVITY OF SEMICONDUCTORS BY ÅNGSTRÖM'S METHOD (934).*

By A. Green and L. E. J. Cowles (Research Laboratories).

Journal of Scientific Instruments, Vol. 37, *pp.* 349-351, *September* 1960.

An apparatus for the accurate determination of the thermal diffusivity of semiconductors, which utilizes the thermoelectric properties of such materials, is described. In its present form, the apparatus can be used between room temperature and 180° C. The application of the method is illustrated by an experiment using a single-crystal specimen of bismuth telluride.

THE ANALYSIS OF BISMUTH TELLURIDE AND RELATED THERMOELECTRIC MATERIALS (947).*

By H. J. Cluley and P. M. C. Proffitt (Research Laboratories).

The Analyst, Vol. 85, No. 1016, pp. 815-822, November 1960.

Methods are presented for analysing thermoelectric materials based on bismuth telluride. The materials examined included modifications of this compound in which bismuth was partly replaced by antimony and tellurium partly replaced by selenium; some materials contained a small amount of iodine.

SWITCHING TRANSISTORS (951).*

By J. N. Barry (Research Laboratories).

Electronic Technology, Vol. 37, No. 12, pp. 442-449, December, 1960.

The various methods used for predicting the performance of switching transistors are described and their validity under conditions of large collector current is discussed. Departures from the behaviour predicted by simple theory have been found, and these are described in some detail. A modified equivalent circuit to represent this behaviour is suggested, and its validity is briefly considered.

The work covers various types of transistor, representing different constructional techniques. It is concluded that at high-current levels evaluation of switching times in terms of the charge control parameters is to be recommended, provided values of these parameters are known which correspond to the currents required in practice.

TRANSPONDER ALTITUDE ENCODERS FOR AIR TRAFFIC CONTROL.

By B. W. Glover (Electronics Division Laboratories).

British Communications and Electronics, pp. 676-680, September 1960.

The Ministry of Aviation has issued development specifications for an experimental system using automatic transmission of altitude data in binary form from an airborne transponder, and this article describes a system that has been developed to meet these specifications.

RECENT ADVANCES IN SOLID-STATE PHYSICS.

By D. A. Wright (Research Laboratories).

Physical Society Year Book, pp. 58-66, 1960.

Recent advances in techniques and in basic knowledge of solid-state physics are outlined, and developments in germanium transistors, parametric and tunnel diodes, switching devices and masers are discussed. The author concludes with a section on the applications of thermo-electricity.

MICROWAVE VALVES: A SURVEY OF EVOLUTION, PRINCIPLES OF OPERATION AND BASIC CHARACTERISTICS.

By C. H. Dix and W. E. Willshaw (Research Laboratories).

The Journal of The British Institution of Radio Engineers, Vol. 20, No. 8, pp. 577-609, August 1960.

After a brief description of the evolution of the different classes of microwave valves, the principal modern types are discussed, under the headings of their mode of operation: 'O' type interaction, 'M' type (crossed field), variable reactance amplifiers; and the maser. A brief survey is given of the performances obtained.

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